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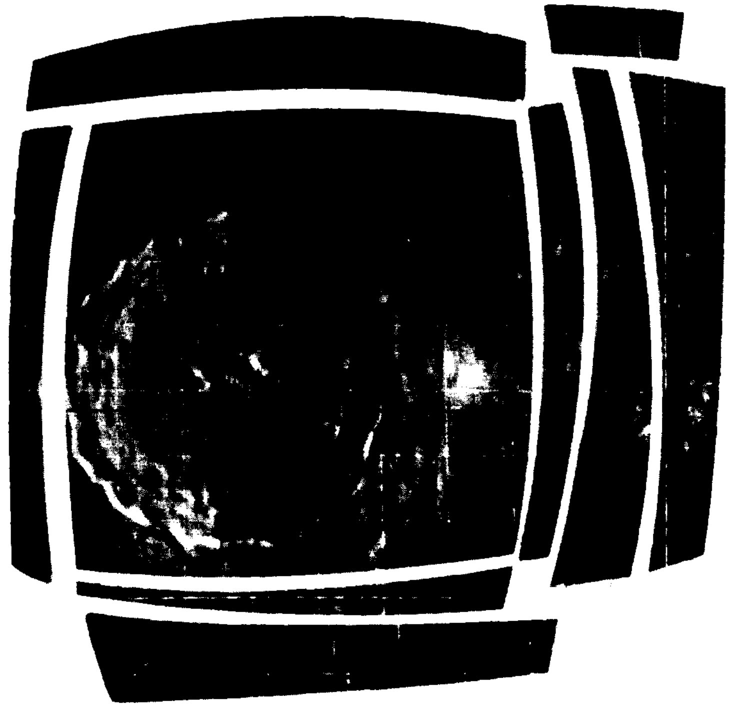

FINAL TECHNICAL REPORT

Surveyor Lunar Roving Vehicle, Phase I

N 66-13451

(ACCESSION NUMBER)	(THRU) 1
124 (PAGES)	(CODE)
CR 68648 (NASA CR OR TMX OR AD NUMBER)	31 (CATEGORY)

FACILITY FORM 602

BSR-903

Volume V
SYSTEM EVALUATION

GPO PRICE $ ________

CFSTI PRICE(S) $ ________

Hard copy (HC) 4.00

Microfiche (MF) 1.00

ff 653 July 65

Bendix SYSTEMS DIVISION

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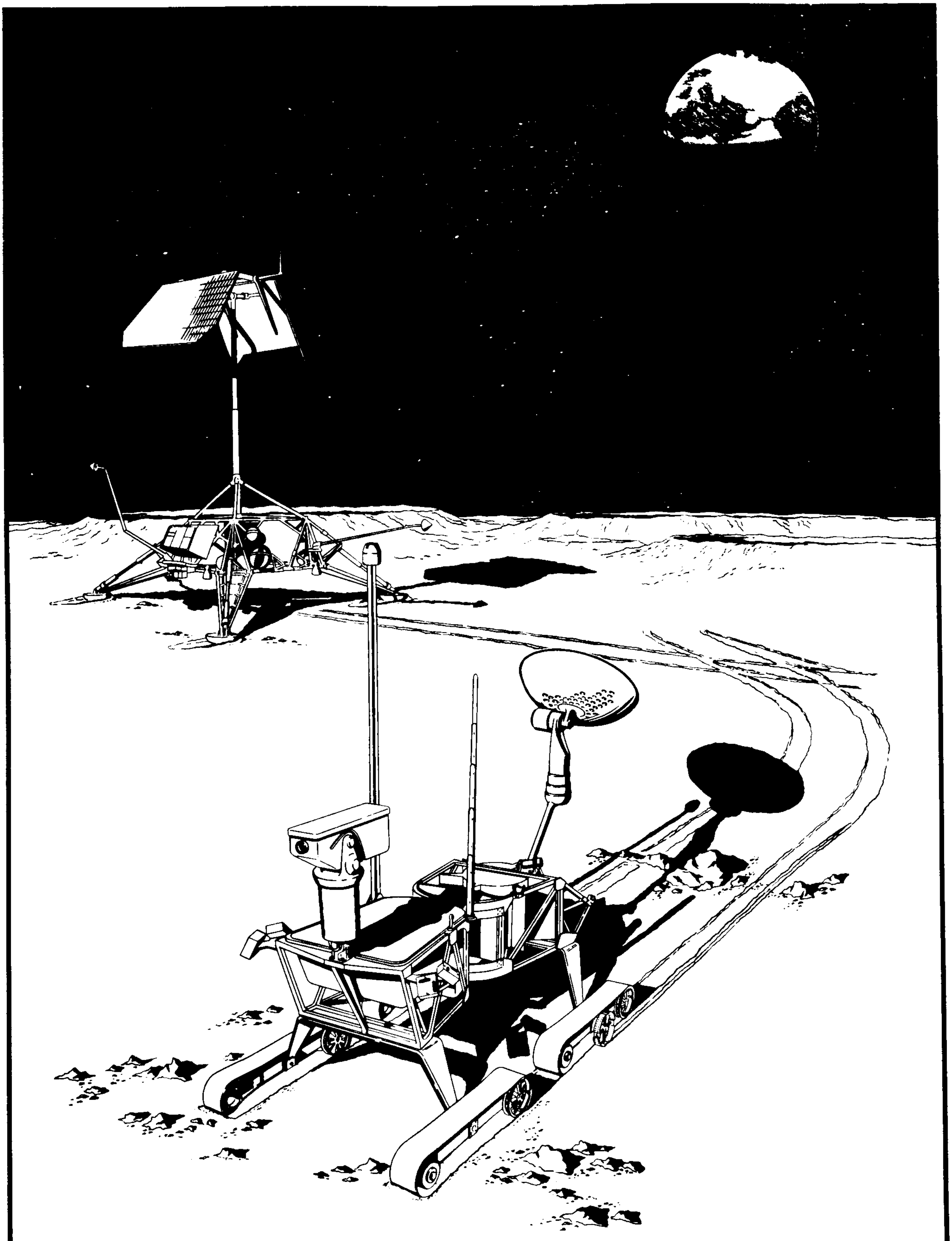

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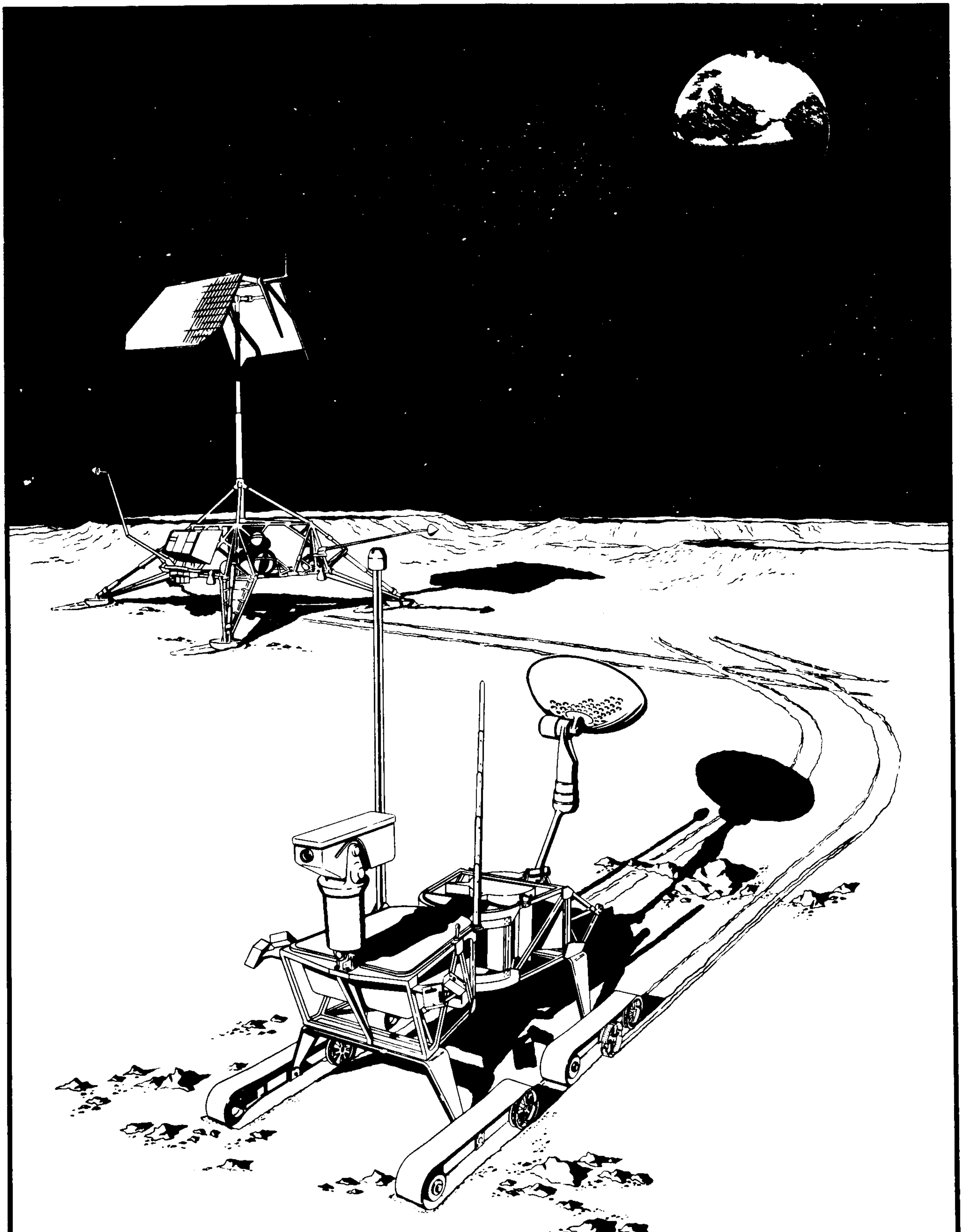

FOREWORD

As part of the continuing program of unmanned exploration of space, and to increase the effectiveness of the manned space program for exploring the moon, the Jet Propulsion Laboratory of the California Institute of Technology issued six-month study contracts to investigate the feasibility of a small, unmanned, lightweight, remotely controlled roving vehicle to be incorporated in the surveyor spacecraft to extend its data-gathering capabilities on the lunar surface. Specifically, the study program was to determine the feasibility of a 100-lb Surveyor Lunar Roving Vehicle (SLRV) system in gathering sufficient scientific information by surveying the lunar surface near the Surveyor spacecraft landing point to certify the area, in terms of specific hazards, as a potential Apollo LEM landing site.

This Final Technical Report, submitted in five volumes, presents the results and conclusions of the study program conducted by The Bendix Corporation under JPL Contract No. 950656. The volumes are organized to correspond to the specific objectives of the program: to conduct an analysis, to generate a preliminary design, and to fabricate and demonstrate an engineering test model in support of the over-all program objectives.

The results of Bendix's study show that the SLRV concept is not only feasible, but can make substantial contributions to the unmanned exploration of the moon in support of the manned Apollo program. The SLRV characteristics, the problems, and the initial trade-offs have been determined in sufficient detail to permit the definition of specific objectives and criteria for a follow-on development program. Program conclusions and recommendations are included in Volume V.

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SECTION 1

INTRODUCTION

This volume of the Final Technical Report presents the results of the Phase I SLRV study program in accordance with the portion of Article 1, Section (a) (1) (iv) of the Statement of Work of JPL Contract No. 950656, Modification No. 1, which states:

> "... calculate the probability that a single roving vehicle system will successfully meet the mission objectives specified in EPD No. 98 for the system, given that the performance of the launching vehicle and the Surveyor spacecraft are within the expected tolerance. In the performance thereof, the Contractor shall:
>
> (A) Analyze the probabilities of meeting partial objectives throughout the roving vehicle mission operational sequence.
>
> (B) Furnish a plan for operating the roving vehicle on the lunar surface. This plan shall include the strategy for choosing between various roving patterns and criteria for changing the pattern depending on the data returned and the possibility of partial failure. The plan shall be coordinated with DSIF capability.
>
> (C) Determine the probability of the roving vehicle certifying the safety of a landing site for the Apollo LEM as a function of the nature of the lunar surface. This study is to take into consideration the mechanical reliability of the rover and the uncertainty in the knowledge of the surface due to finite sampling, imperfect measurements etc. The criteria for certification is given in EPD-98."

In addition, an evaluation of the performance of SLRV systems for gross weights in excess of 100 lb is given, as well as the results of tests conducted during the study program on an engineering test model designed and fabricated to demonstrate mobility and maneuverability capabilities and limitations of the 100-lb design.

SECTION 2

MISSION EVALUATION

This section presents an evaluation of the SLRV Mission in support of the Apollo program, relative to similar missions of other existing programs. The primary objective of this evaluation is the establishment of the required SLRV system probability of success (P_s) for the site verification mission by comparison with the relative capability of other systems to accomplish the same objectives.

Specifically, the mission of site verification has been defined in terms of the data to be collected on the bearing strength of the lunar soil, small-scale topography (in the region of 25 cm to 1 meter), and slope in the potential site area.

2.1 EFFECTIVENESS DEFINITION

The approach to mission evaluation is to establish an effectiveness criteria (E) such that

$$E = \frac{G_p \times P_p}{C_r} . \qquad (2.1\text{-}1)$$

where

G_p = the mission defined above

P_p = the probability of a given diagram accomplishing this mission

C_r = the cost of accomplishing the mission in terms of time and dollars.

Since all existing lunar-oriented systems such as Surveyor A, LOS, etc., can provide some measure of G_p for some established or predicted cost, and at some period of time prior to the manned landing mission, then E, the comparison variable, may be established for all existing systems.

Assuming that an increase in the value of E by a factor of 4 over other systems is a criteria for continued development of the SLRV Program, then four times the maximum effectiveness determined for any of the other systems would be used in Equation (2. 1-1) to determine the value of P_p required for SLRV.

The comparison to SLRV may be made for each other program separately or against all other programs in combination.

The following sections develop the complete definitions of the mission (G_p), the effectiveness criteria (E), and the cost factor (C). This is followed by the derivation of E for each of the other competing systems. The section will be concluded with the calculation of the required effectiveness (E) and, hence, P_s for SLRV, where P_s is one term in the program probability (P_p) defined above.

2.1.1 Defined Mission Term

The mission term, G_p, is defined to include the type, quantity, and quality of data necessary to certify a landing site for Apollo with a confidence of 99%.

The data required are defined as follows:

1. Determination of effective protuberances of 50 cm or greater where an effective protuberance is defined as the surface and/or subsurface relief within a horizontal distance of approximately 10 meters which might cause the bottoming and/or tilting of the LEM. Effective protuberances may result from single objects or complex combinations of heights, depressions, and surface sinkages. The maximum relief contributed by a single protuberance or combination of protuberances and depressions may range from 20 to 50 cm.

2. The determination of effective slopes of 12° or greater where an effective slope is defined as the general surface slope over an area too large for the LEM to straddle, plus the combined effects of superimposed heights, depressions, and surface sinkage.

3. The determination of surface bearing strengths which will permit sinkage of no greater than 10 cm for a 1.0-psi static load or sinkage no greater than 30 cm for a dynamic load of 12 psi at an impact velocity of 3 meters per second.

These data must be collected in sufficient quantity and quality to ensure with 90% confidence that 95% of a 3200-meter diameter site is acceptable and that 70% of this site is acceptable with 99% confidence. Since a site which satisfies these requirements will provide a probability of a successful LEM landing (P_L) of 0.99, this value is used as the maximum value for G_P.

The measurements of soil, slope, and protuberance characteristics are considered of equal importance to the probability of a successful LEM landing for lack of any other justifiable weighting. It has therefore been assumed that the determination of any two of the three characteristics satisfying the confidence levels noted above will result in a value for G_P of 0.66 and that the determination of any one of the three characteristics defined above will result in a value of G_P equal to 0.33.

2.1.2 Cost

In establishing a relative cost figure, two measures of cost are considered significant. First is the development and operational cost of the programs to be considered for evaluation, and second is a measure of the potential cost incurred caused by a slippage in the Apollo manned-landing launch date -- if it is determined that the lunar surface characteristics are such that an unreasonably low confidence in landing exists with the current Apollo design.

It must be assumed that confidence in the ability of the Apollo LEM to land successfully is equal to the confidence in the knowledge of the acceptability of the landing site. For example, at the present time, confidence in the ability of the LEM to land on the moon must be considered to be quite low, since there is no knowledge of the small-scale terrain characteristics of any portion of the lunar surface. Therefore, there is as much probability that no acceptable landing site exists as there is the probability that an acceptable landing site does exist.

To explore this approach to the measure of cost, consider the following. If no program prior to the launch of the manned-landing mission is successful, then even if the Apollo LEM had the capability to measure the terrain characteristics as defined in Section 2.1.1 above, confidence in the ability to make a successful landing must still be considered low since there is no prior knowledge that such a landing site exists. On the other hand, if one or more lunar exploratory systems is successful several years prior to the manned landing, then a high degree of confidence will exist in the findings of that system. If the system data indicate that a large percentage of the moon's surface is acceptable in terms of the Apollo LEM landing characteristics, then a high degree of confidence in a successful LEM landing exists. In the event the data returned by this early exploratory system indicates that only a small percentage of the actual surface is acceptable to Apollo, then sufficient time would exist to take several courses of action. Examples would be improving the maneuvering capability of LEM or modifying the LEM landing system to accommodate the more rugged terrain. In either case, the delay in the launch date of the man-landing program would be minimal, and the additional cost would be small compared to the cost of delaying the entire Apollo program, which would occur if this information were not obtained until the time of the first manned landing attempt.

For the purpose of evaluation, it has been assumed that it would require approximately one year to modify the Apollo system either to improve its navigation capability or to improve the landing gear, and that the cost value of slippage in the Apollo launch date is one billion dollars/year. Therefore, the measure of cost in evaluating any system will include not only the development and operational cost, including the total number of flights postulated for that system, but also an "effective" cost term reflecting the amount of time prior to the first manned landing that the system completes its mission. Figure 2.1-1 illustrates the cost relationship which is also expressed below.

$$C_R = \frac{(1 - t_{BL})\, 10^9 + C_x}{C_A} \qquad (2.1\text{-}2)$$

V

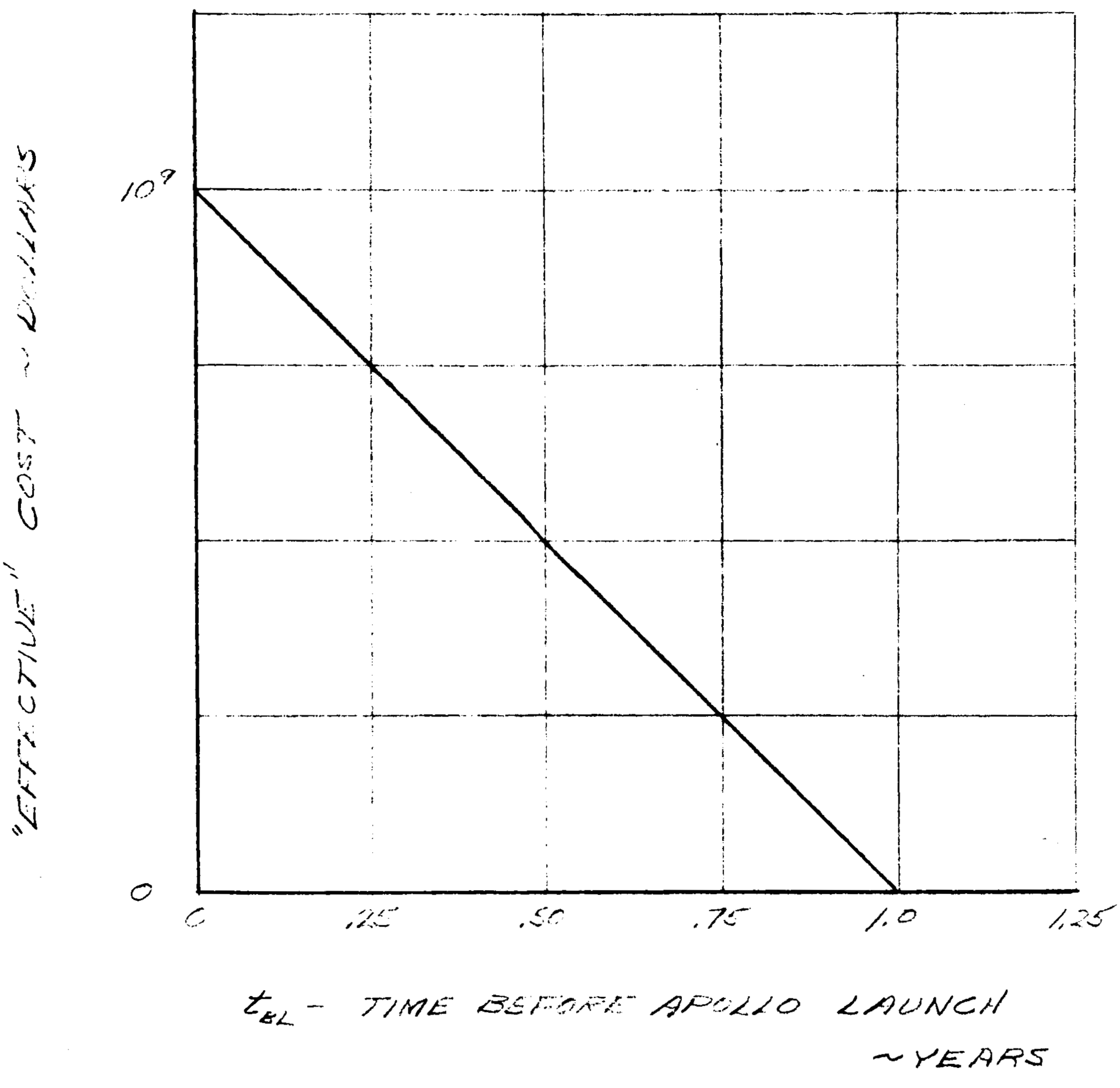


Figure 2.1-1 Effective Cost vs Time Before Apollo Launch

where:

C_X = development and operational cost of program
C_A = cost of one Apollo manned launch
t_{BL} = time of launch before Apollo launch (years) $\leqq 1$

Based upon Equation 2.1-2, it may be seen, for example, that the "cost" term (when determining the effectiveness of the Apollo LEM to find its own landing site without prior exploration) would include the normalized development cost factor, which in this case is unity, plus the normalized maximum increase caused by a one-year delay of one billion dollars divided by the development cost of the Apollo program. Conversely, System X, which is developed and operational, say, more than one year prior to the manned landing ($t_{BL} = 1.0$), would have as its cost term its development and operational cost normalized to the cost of Apollo without the addition of delay cost. This follows since the findings of this program with respect to the acceptability of the lunar surface, whether good or bad, would be known in time to make the necessary modifications to Apollo without an appreciable cost increase.

2.1.3 Probability of Success

Success probability involves two factors: (1) the probability that the equipment does not fail (mechanical reliability), and (2) the probability that equipment performance will be within the tolerances established for the design.

2.1.4 Effectiveness Level

The programs to be considered in terms of their effectiveness for Apollo landing site verification are:

1. Surveyor Lunar Roving Vehicle
2. Surveyor A
3. Lunar Orbiting Satellite
4. A manned Lunar Orbiter, termed Apollo B
5. Second Generation LRVs.

2.2 ANALYSIS OF COMPETITIVE PROGRAMS

2.2.1 Apollo LEM

In evaluating the Apollo LEM capability of verifying its own landing site, it is to be expected that the LEM crew will have an adequate capability of small-scale relief and slope detection, but not capability for soil bearing strength measurement. The mission terms in percentage are then

$$G_{P_{OB}} = 33$$

$$G_{P_{SL}} = 33$$

$$G_{P_S} = 0$$

The proability of success in detection of these hazards by the LEM will be assumed to be unity, or $P_P = 1.0$.

By definition, the time before launch for LEM, t_{BL}, = 0.

The cost of one Apollo launch (development and operation) is estimated to be $100,000,000.

Therefore, the effectivenss is calculated from Equations 2.1-1 and 2.1-2:

$$E = \frac{(0 + 33 + 33)(1.0)}{\left[\frac{(1 - 0)10^9 + 10^8}{10^8}\right]} = 6.0 \ .$$

2.2.2 Lunar Orbiting Satellite (LOS)

The Lunar Orbiting Satellite will have a capability of resolving objects down to 1 meter. Since resolution of 0.25 meter or less is required for LEM landing site verification, the LOS has no capability to determine the required small-scale relief. The LOS also will have no capability for soil bearing strength determination. Slope measurements will have an accuracy of approximately $\pm 6^\circ$. However, since the LOS will view a very large amount of the lunar surface, a LEM landing site with acceptable slopes will be identifiable. Summarizing, $G_{P_S} = 0$; $G_{P_{OB}} = 0$; $G_{P_{SL}} = 33$.

Based on ten launches, the LOS probability of success $P_P \cong 1.0$.

The data will be obtained at least one year prior to the first Apollo launch and therefore $t_{BL} = 1.0$.

The cost of the LOS program is estimated to be $100,000,000. Therefore,

$$E = \frac{(0 + 0 + 33)(1.0)}{\left(\frac{0 + 10^8}{10^8}\right)} = 33.0 \ .$$

2.2.3 Surveyor A

Figure 2.2-1 shows that a 0.71 LEM landing success probability is associated with one 60-meter diameter LEM landing point. Since this is approximately the limit of the Surveyor A's TV survey range, the following data gathering capabilities can be calculated

$$G_{P_{OB}} = 0.71 \times 33 \cong 23.5$$

$$G_{P_{SL}} = 0.71 \times 33 \cong 23.5 \ .$$

The confidence gained by bearing strength measurements in only one position is very low and is assumed to be 10% of the desired value. Therefore

$$G_{P_S} = 0.1 \times 33 = 3.3 \ .$$

With seven or more flights, a high program probability of success will be obtained. If the single launch probability of success is 0.5, then the program probability of success for seven flights is 0.99 and will be assumed to be unity.

The Surveyor A program will be completed more than one year before the first Apollo launching and, therefore, $t_{BL} = 1.0$.

Estimated cost of the program is $ 250,000,000.

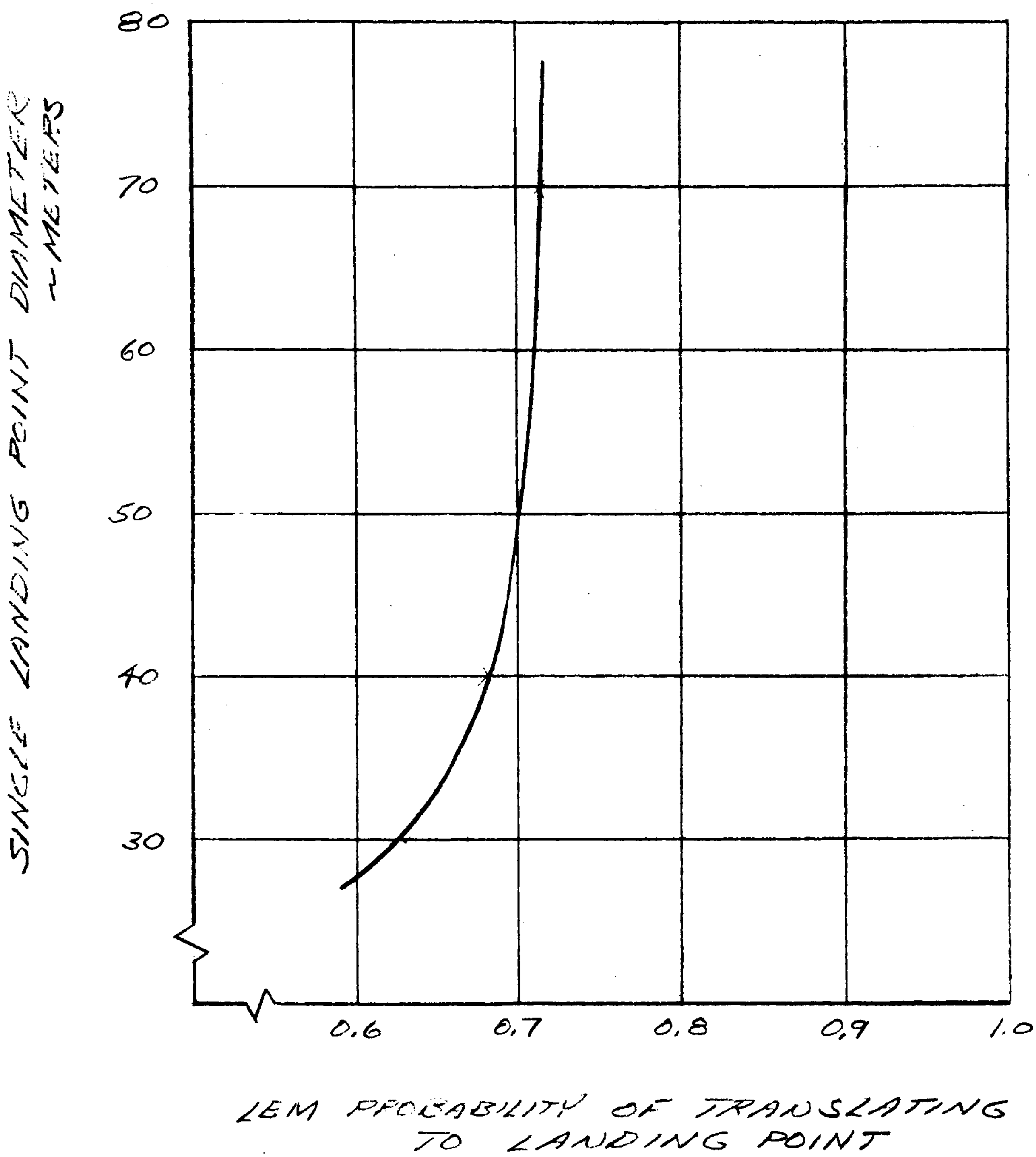


Figure 2.2-1 Single Landing Point Diameter vs LEM Probability of Translating to Landing Point

Therefore

$$E = \frac{(3.3 + 23.5 + 23.5)(1.0)}{\left(\frac{2.5 \times 10^8}{10^8}\right)} = 20.2 \ .$$

2.2.4 Apollo B

The Apollo B, taking high-resolution pictures from orbit, will have the full capability of small-scale relief and slope detection required for site verification, but no capacity for soil bearing strength measurement.

A program probability of success equal to that of other manned missions ($\cong 1.0$) will be assumed.

The time before Apollo launch is taken as 0.5 year, and the estimated cost is \$75,000,000 for a single flight (development costs are essentially accounted for in the normalized LEM cost). Then:

$$E = \frac{(0 + 33 + 33)(1.0)}{\left[\frac{(.5)10^9 + (7.5 \times 10^7)}{10^8}\right]} = 11.5 \ .$$

2.2.5 Second Generation LRV

A second generation LRV, in a weight class requiring a larger launch vehicle than SLRV, would possess a full capability for LEM landing site verification in all three hazard classes.

The single launch probability of success is taken to be 0.5. However, it is assumed there will be two flights, making the program probability of success 0.75.

Since this would be a new development program, it is assumed the data would not be received until 0.5 year before the first Apollo launch. The estimated program cost is \$400,000,000.

Therefore

$$E = \frac{(100)(0.75)}{\left[\frac{(0.5)10^9 + (4 \times 10^8)}{10^8}\right]} = 8.4 \ .$$

2.3 SLRV PROGRAM PROBABILITY OF SUCCESS

It has been stated that the SLRV must possess an effectiveness four times as great as any of the competitive programs. It has been shown that the LOS has the highest effectiveness of the competitive programs (33.0). Therefore, the SLRV program effectiveness must be 132.

The SLRV has a complete capacity for the LEM site verification mission ($G_P = 1.0$).

For SLRV, $t_{BL} = 1.0$, and the program cost is estimated at $50,000,000.

The expression for program probability of success is then

$$132 = \frac{(100)\ P_P}{\left(\frac{(5 \times 10^7)}{10^8}\right)}$$

or, the required program probability of success is 0.66.

2.4 SLRV SINGLE LAUNCH PROBABILITY OF SUCCESS

The relationship between the program probability of success and the single launch probability of success is

$$P_P = 1\,(1 - P_{SSL})^n$$

where

P_P = program probability of success

$P_{S_{SL}}$ = probability of success of a single launch

n = number of launches.

For the SLRV, n is taken to be eight. Therefore:

$$(1 - P_{S_{SL}})^8 = 1 - 0.66 = 0.34$$

From which a required single launch probability of success of 0.13 is calculated.

2.5 ROVING VEHICLE PROBABILITY OF SUCCESS

The single launch probability of success, $P_{S_{SL}}$, is comprised of three terms:

1. Atlas-Centaur success probability
2. Surveyor landing success probability
3. Roving vehicle success probability.

The Atlas-Centaur probability of success, estimated for the time period when the SLRV will be operational, is 0.7.

The success probability for Surveyor is assumed to be 0.5.

Therefore

$$0.13 = (0.7)(0.5) P_S$$

where

P_S = the required roving vehicle probability of success solving, $P_S = 0.372$. This value of the roving vehicle probability of success is therefore the criteria against which the system evaluation is made.

SECTION 3

EVALUATION OF 100-LB SYSTEM

3.1 EVALUATION SIMULATION

Appendix A of EPD-98, Revision 1, requires that the SLRV system be capable of verifying that the lunar landing site meets LEM requirements within the following limits:

1. A 99% confidence that 70% of the area within the site is acceptable.
2. A 90% confidence that 95% of the area within the site is acceptable.

Volume II of this report shows that these requirements can be met with a SLRV mission defined as the capability of verifying with 99% confidence a series of points, each 40 meters in diameter, and distributed in a preset pattern throughout the 3200-meter site. The minimum number of acceptable points is stated as 13, with the desired SLRV mission requiring a capability of verifying 19 points.

The evaluation simulation is designed to determine the probability of success of completing this mission as well as the partial missions comprising less than 19 points. This determination is obtained as a function of the lunar surface, considering reliability, finite sampling, and perfect measurements.

3.1.1 Evaluation Approach

The ideal approach to the evaluation might involve displays, terrain maps, etc. Such an approach, however, is time-consuming and costly and is more in keeping with operator training than initial system evaluation. The approach taken here is the use of a Monte Carlo simulation wherein the statistical nature of the system variables, e.g., terrain and reliability, may be preserved without requiring real-time solutions which would be likely in the more sophisticated approach. The Monte Carlo simulation is a proven technique for treating a statistical problem and may be tailored to any degree of sophistication desired, limited only by available knowledge of the events of the problem and the distributions describing their frequency of occurrence. The number of computer runs required is higher than for deterministic programs, but is not unduly large when compared to real-time evaluation.

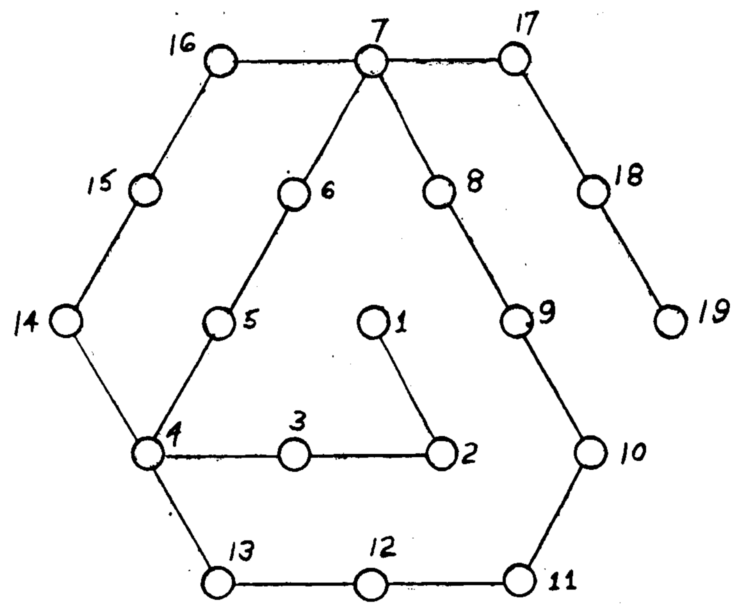
Basically, the SLRV is evaluated as to its ability to verify 19 points in the pattern indicated in Figure 3-1(a). In the simulation, this pattern is, in concept, laid out in a straight line as in Figure 3-1(b) such that direction of travel and point location are not accounted for. This simplified approach avoids consideration of the direction (left or right) to be taken on encountering impassable areas. Such an accounting is really in keeping with a simulation involving terrain maps, which are not used here. By ignoring the position of the points relative to the pattern center (the LEM aiming point), the fact that points close to the center are more valuable than those on the periphery is being ignored. Thus, each point is weighted equally which is somewhat short of the true picture. Figure 3-2 shows the relationship between P_{TS} and the diameter of the veritied site. P_{TS} is defined as the probability that the LEM, after arriving at hover altitude, is capable of translating to a surveyed point. From Figure 3-2 it is readily seen that verification of points close to the aim point at the pattern center contribute greatly to the LEM success probability. As points further from the center are verified and the verified diameter increased, the probability increment decreases. Ignoring this trend by weighting all points equally is not a serious simulation fault at this stage, but should be incorporated if variable strategy is introduced.

Referring once more to Figure 3-1(b), it is seen that the entire mission of verifying 19 points is a repetition of the two major events:

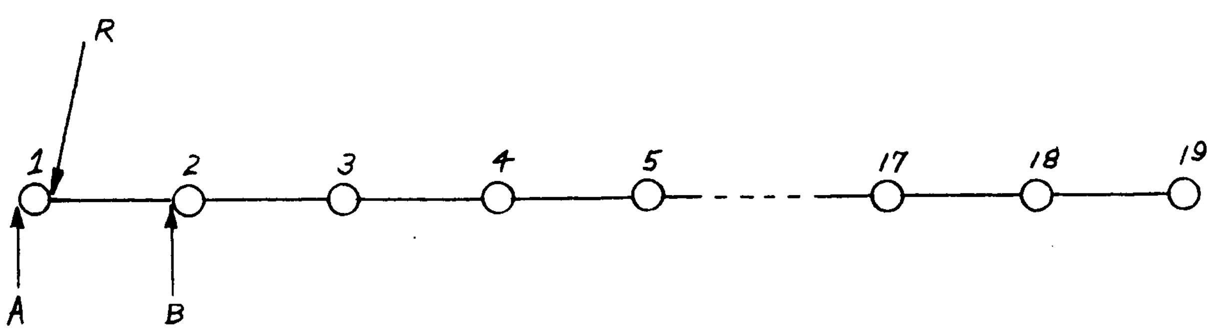
1. Point survey

2. Interpoint travel.

Thus, the simulation is set up to cover the cycle from A to B, as shown, with 19 cycle repetitions for one mission. During each cycle, reliability data will be checked following the point survey, at times marked "R" in



(a)



(b)

Figure 3-1 Simulation Concept

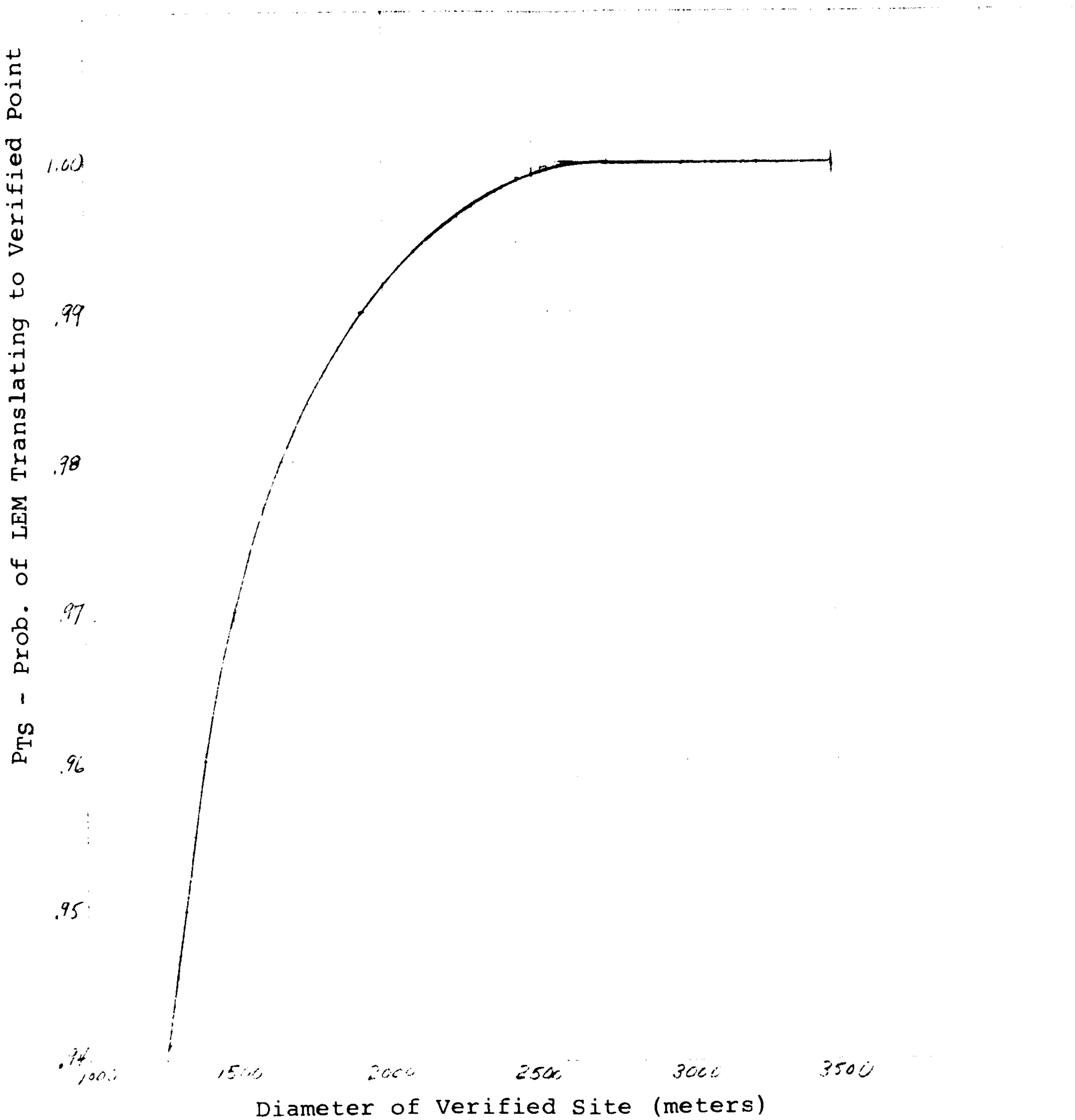


Figure 3-2 Relationship Between P_{TS} and Diameter of Verified Site

Figure 3-1(b). To accomplish the computation of each cycle, the information flow is as shown in Figure 3-3. The simulation for one mission consists of 19 times through the flow chart. After initial setup, a point survey is conducted and the marking schedule consulted to determine if marking is required. Operational constraints such as DSIF availability and lunar night are then examined and the mission time adjusted accordingly. The operational status is then checked by testing for failures. If 19 points have been completed, the mission is over and the simulation completed. Otherwise, the SLRV completes the point by travelling to the next point, corresponding to point B of Figure 3-1(b). The simulation then returns to "point survey" to start the following cycle.

Several of the routines indicated involve statistical quantities. Thus, by making a large number (100) of runs and tabulating the number of missions wherein 19 sites are completed, the probability of mission success is then computed as the ratio of the completed missions to the total number of tries (runs). Partial objectives, i.e., for 18, 17, 16 points, etc., are obtained in like manner.

3. 1. 2 Simulation Details

This section presents in detail the content of the simulation at its present stage of development. Section 3. 1. 2. 1 presents a narrative description of the information flow; the inputs are discussed both as to form and derivation in Section 3. 1. 2. 2; finally, Section 3. 1. 2. 3 discusses the manner of introducing failures, both catastrophic and partial.

3. 1. 2. 1 Simulation Logic

The details of the simulation are shown in Figure 3-4. Major inputs are shown on the left, the program logic in the center, and major outputs in the right-hand columns. The logic, as shown in the center portion, may be related directly to the boxes indicated in Figure 3-3 and are so numbered. The major input variables are the surface model, operational constraints, reliability, and LEM and SLRV capabilities. Any of these may be perturbed to exercise the model. Various other relationships are required for distance and time computations. These are discussed in detail in Section 3. 1. 2. 2. The major outputs are the number of points verified, and mission time and distance. A description of the complete program follows, moving down from the top of Figure 3-4.

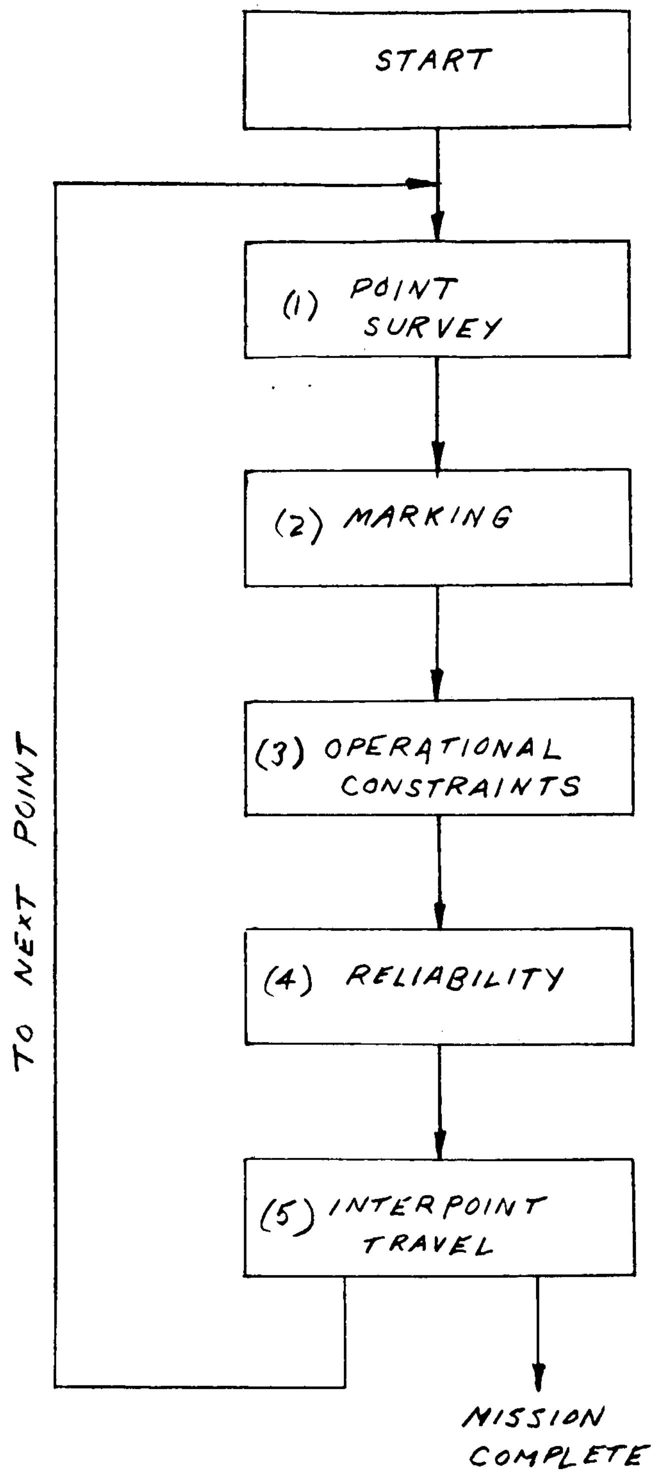
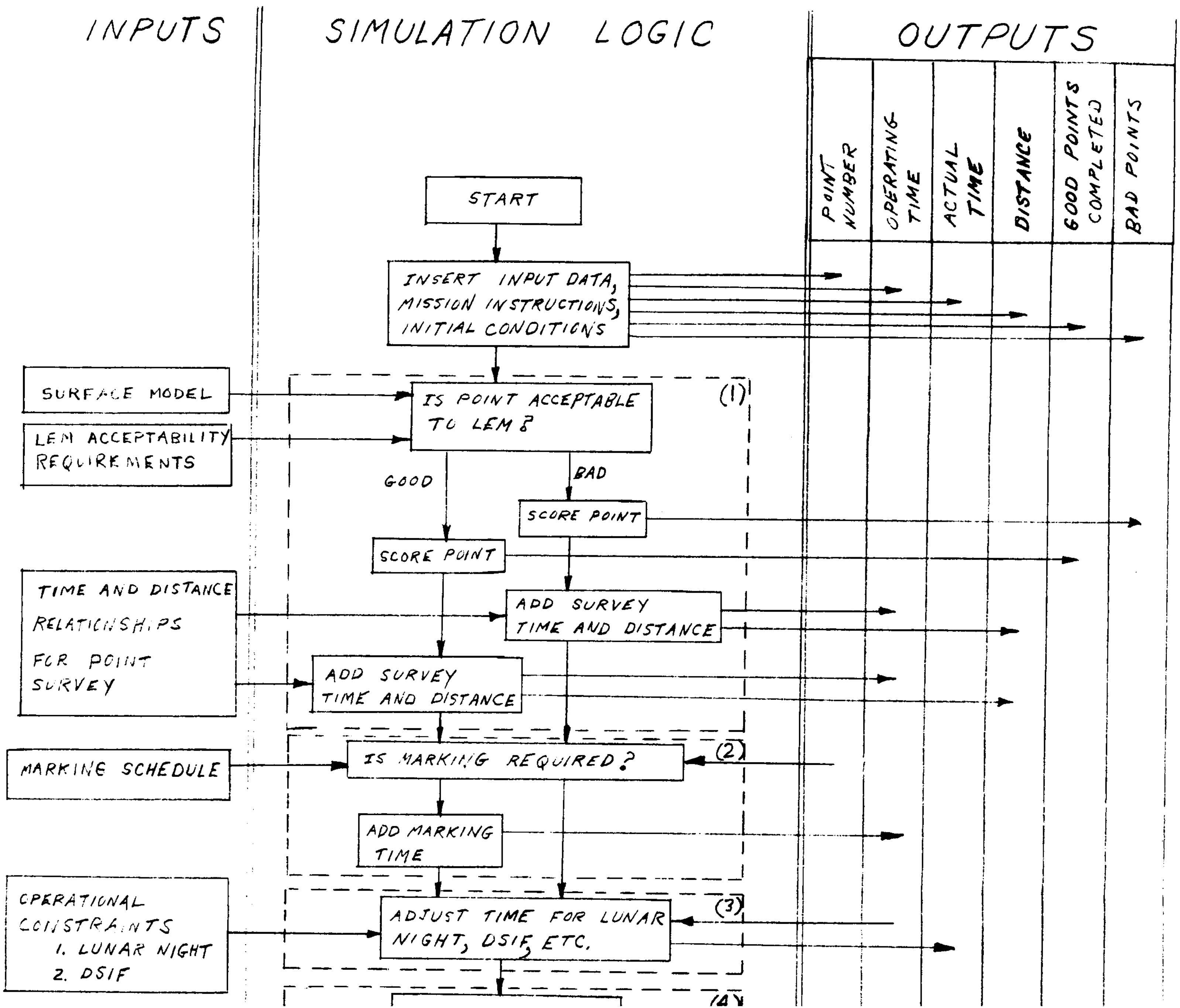


Figure 3-3 Simulation Flow Chart


INPUTS
SIMULATION LOGIC
OUTPUTS
POINT NUMBER
OPERATING TIME
ACTUAL TIME
DISTANCE
GOOD POINTS COMPLETED
BAD POINTS
START
INSERT INPUT DATA, MISSION INSTRUCTIONS, INITIAL CONDITIONS
SURFACE MODEL
LEM ACCEPTABILITY REQUIREMENTS
(1)
IS POINT ACCEPTABLE TO LEM?
GOOD
BAD
SCORE POINT
SCORE POINT
TIME AND DISTANCE RELATIONSHIPS FOR POINT SURVEY
ADD SURVEY TIME AND DISTANCE
ADD SURVEY TIME AND DISTANCE
MARKING SCHEDULE
(2)
IS MARKING REQUIRED?
ADD MARKING TIME
OPERATIONAL CONSTRAINTS
1. LUNAR NIGHT
2. DSIF
(3)
ADJUST TIME FOR LUNAR NIGHT, DSIF, ETC.
(4)

V

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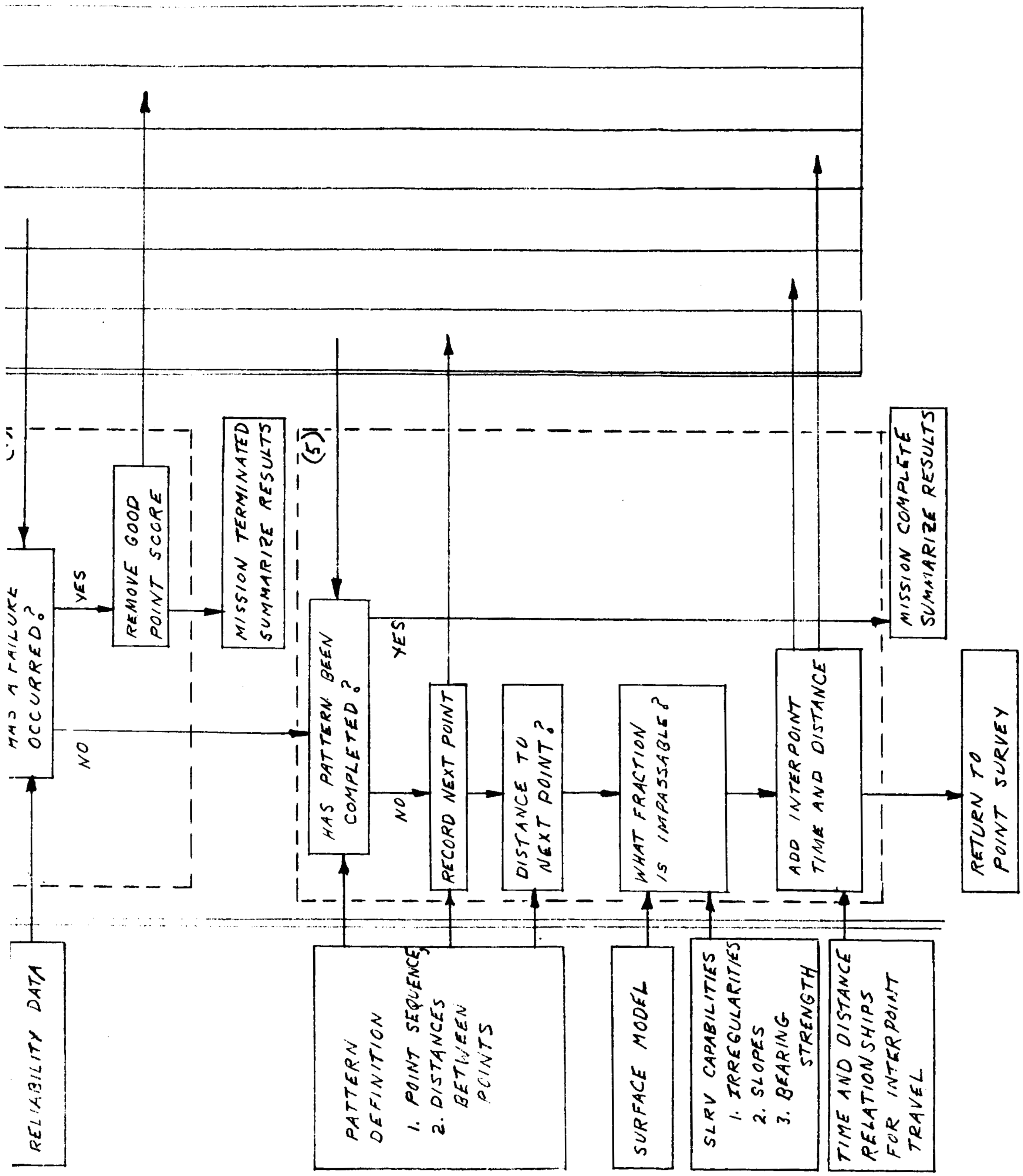

Figure 3-4 Simulation Details

2#

Following initial setup, which need not be discussed, the first point survey is conducted. This consists of determining whether the point is acceptable for LEM landing by comparing the surface model to LEM requirements. Because the SLRV terrain capabilities are greater in every particular than the LEM landing requirements, the question of whether the SLRV can traverse the point need not be considered. Every acceptable point can be traversed, and unacceptable points can be traversed to the extent required for rejection.

Both good and bad points are tabulated as indicated and a suitable time and distance added for the point verification. The time and distance added are different for good and bad points, since a bad point need not be covered in total on the average. The details of the time and distance computations are given in Section 3. 1. 2. 2 under the heading "Time, Distance Relationships—Point Survey".

Since the mission requirements may include marker emplacement in the absence of suitable landmarks, a marking subroutine has been included. From the basic pattern being followed, a marking schedule is developed. The subroutine simply consists of checking to see whether marking is called for. If required, a standard time increment is added to the operating time. The assumption is made that no additional travel range is required for marking, i. e., that the marker is emplaced at a point.

The next simulation event is to include the operational restrictions of lunar night and DSIF availability. Up to this point in the simulation, all elapsed time has been entered in the "operating" time column which omits such considerations. The accumulated operating time is now read out and, by comparing with the operational schedule data, adjusted to include these considerations. This adjusted time is now termed "actual time" and is entered as shown.

The reliability corresponding to this actual time is then determined and a test for failures is made. Suppose for discussion purposes that a catastrophic failure has occurred. In this case, the surveyed point is removed from the "good" tabulation, and the output data are summarized and printed. If no failure has occurred, the SLRV proceeds to the next point.

Upon referring to the pattern definition, it may be that the pattern has been completed; in this case, the results are tabulated. Otherwise, the destination point is recorded as being the next survey point and the distance to that point determined. Even with constant spacing between points, the distance to the next point may vary. In Figure 3-1(a), for example, moving from 13 to point 14 requires covering double the usual interpoint distance.

The surface model is then compared with SLRV capabilities to determine how much of the area ahead is impassable. The time and distance of travel are then computed and added to operating time and elapsed distance. Relationships used in this calculation are discussed in Section 3. 1. 2. 2 under the heading "Time, Distance Relationships—Interpoint Travel".

After the interpoint is completed, the simulation then returns to the point survey, with the point to be surveyed having been updated and elapsed time and distance recorded. Thus, it is seen that 19 passes through the computer logic will correspond to one mission, the survey of 19 points. DSIF and Lunar Night constraints are inserted each cycle, and the possibility of failure is likewise evaluated each cycle.

3. 1. 2. 2 Inputs

The inputs to the simulation will be discussed in the order shown in Figure 3-4 from top to bottom. The form of the inputs will be discussed and, where applicable, the analysis or justification for particular approaches or values will be indicated.

Surface Models

The selection of suitable surface models was based on the following:

1. The range of models should cover the total spread of models detailed in EPD-98 Revision 1, from the most favorable to the most adverse combination.

2. Any single model must contain some terrain acceptable to LEM. Otherwise, the probability of success, being dependent in part upon LEM requirements, would be zero.

3. The number of models should be limited by requiring that no model be justified unless it differs by an order of magnitude from all others in at least one particular.

Three quantities or particulars were used to describe a model:

(1) irregularities (includes obstacles and crevices),

(2) slopes, and

(3) bearing strength.

These were converted to the following descriptors:

(1) smooth vs rough,

(2) flat vs steep, and

(3) hard vs soft.

The most favorable model may then be described qualitatively as smooth, flat, and hard; mission time over this surface would be a minimum. The most adverse model could then be described as rough, steep, and soft; maximum mission time should result.

A quantitative definition of the above terms is arbitrary in the absence of measured lunar surface data. The extreme values (based on EPD-98) were selected as follows:

1. Max irregularities - 100 cm

2. Max slopes - 15°

3. Min bearing strength gradient - 1 psi/ft.

The assumed distribution of various intermediate magnitudes would probably differ greatly from one investigator to another. Also, it is recognized that the assumed distributions are ultimately reflected in the mission success probability. Some assumption on distribution is necessary, however. It seems likely that all magnitudes of hazards between the extremes may be expected. Therefore, the distributions assumed in the study provide for intermediate values in approximately equal amounts. Thus, the definition of "rough" is as shown in Figure 3-5, with maximum irregularities of 100 cm and significant amounts of lesser magnitudes. This type of model will show the effect on mission success of changes in, for example, mobility capability, since as capability grows, the percent of impassable area decreases with a resultant shortening of both mission range and time. The definition of "smooth" is derived by decreasing each irregularity size found in the "rough" definition by approximately an order of magnitude. It might be noted that the selected smooth model presents no problems for either the 100-lb SLRV or the LEM landing. The rough surface presents problems for both; about 40% is impassable for the SLRV, about 20% is unacceptable to LEM.

The definition of "flat" vs "steep" is shown in Figure 3-6. Again, the maximum value of 15^{o} is taken from EPD-98, and lesser slopes are distributed in approximately equal amounts. The flat model is then derived by reducing the steep one by an order of magnitude. For the 100-lb SLRV, the steep model presents no impassable slopes. However, since the present LEM requirement is set at 12^{o}, about 10% of the slopes are unacceptable. Any point containing these will then be rejected during the "point survey" subroutine.

In considering bearing strength gradient, EPD-98, Revision 1, calls out a minimum of 1 psi/ft for the soft model. This is taken as the extreme value of Figure 3-7. Increased values are assumed to occur, and the maximum value of 20 psi/ft in the soft model is well above the acceptable limit for LEM. If the soft model had no acceptable areas, all points would be rejected during "point survey", and the probability of success for any surface model containing the "soft" definition would be zero. Therefore, the soft model was set up so that 70% is acceptable to LEM. The "hard" definition is then derived by increasing the bearing strength gradient of the soft model by about an order of magnitude. This results in a model totally acceptable to LEM.

The extreme models just discussed satisfy the first two requirements outlined. The number of necessary intermediate models required is then easily shown to be six. By changing one particular at a time in the most favorable model (No. 1) to the adverse condition, models 2, 3, and 4 are generated. Thus,

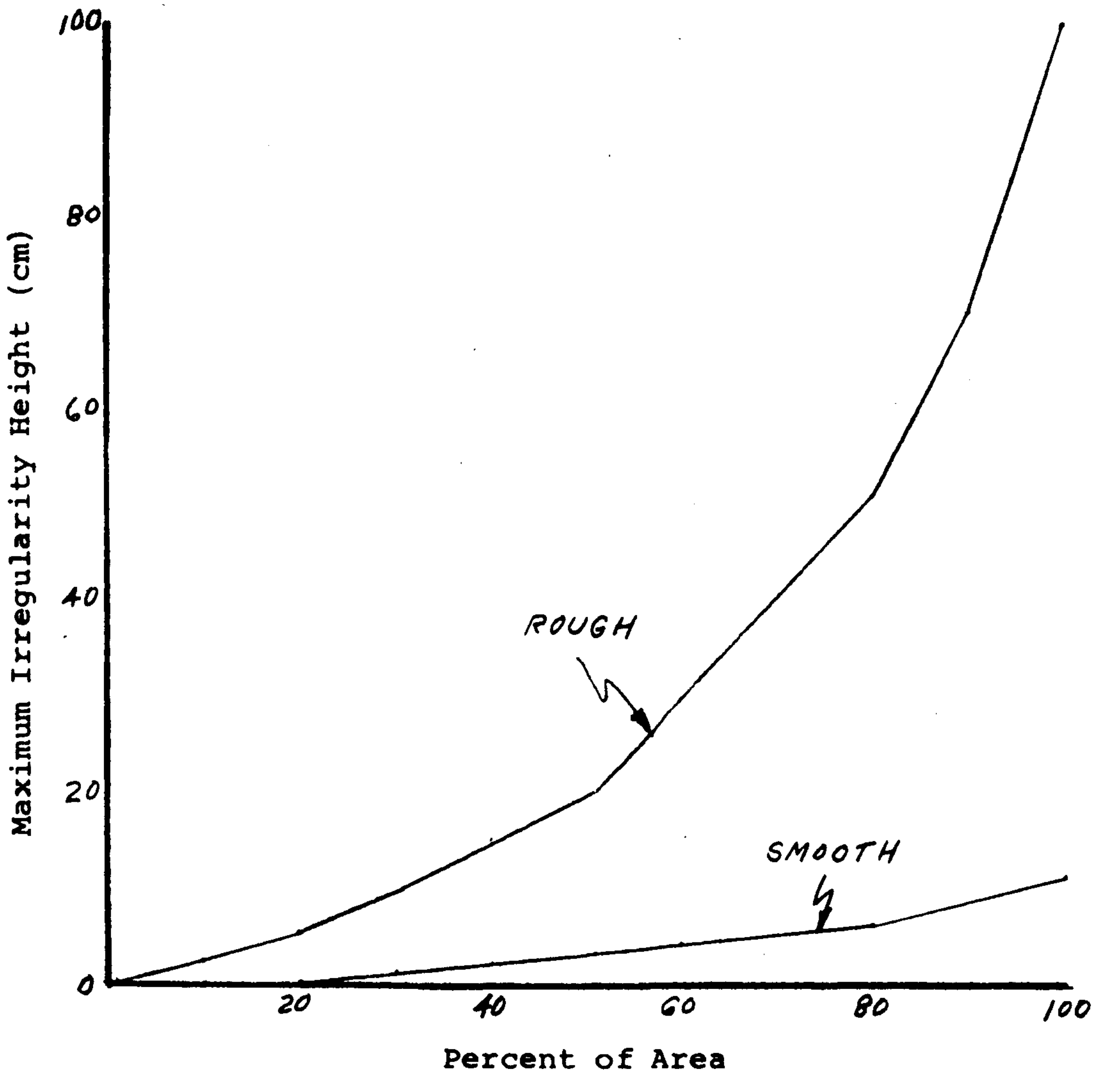

Figure 3-5 Definition of Irregularity Models

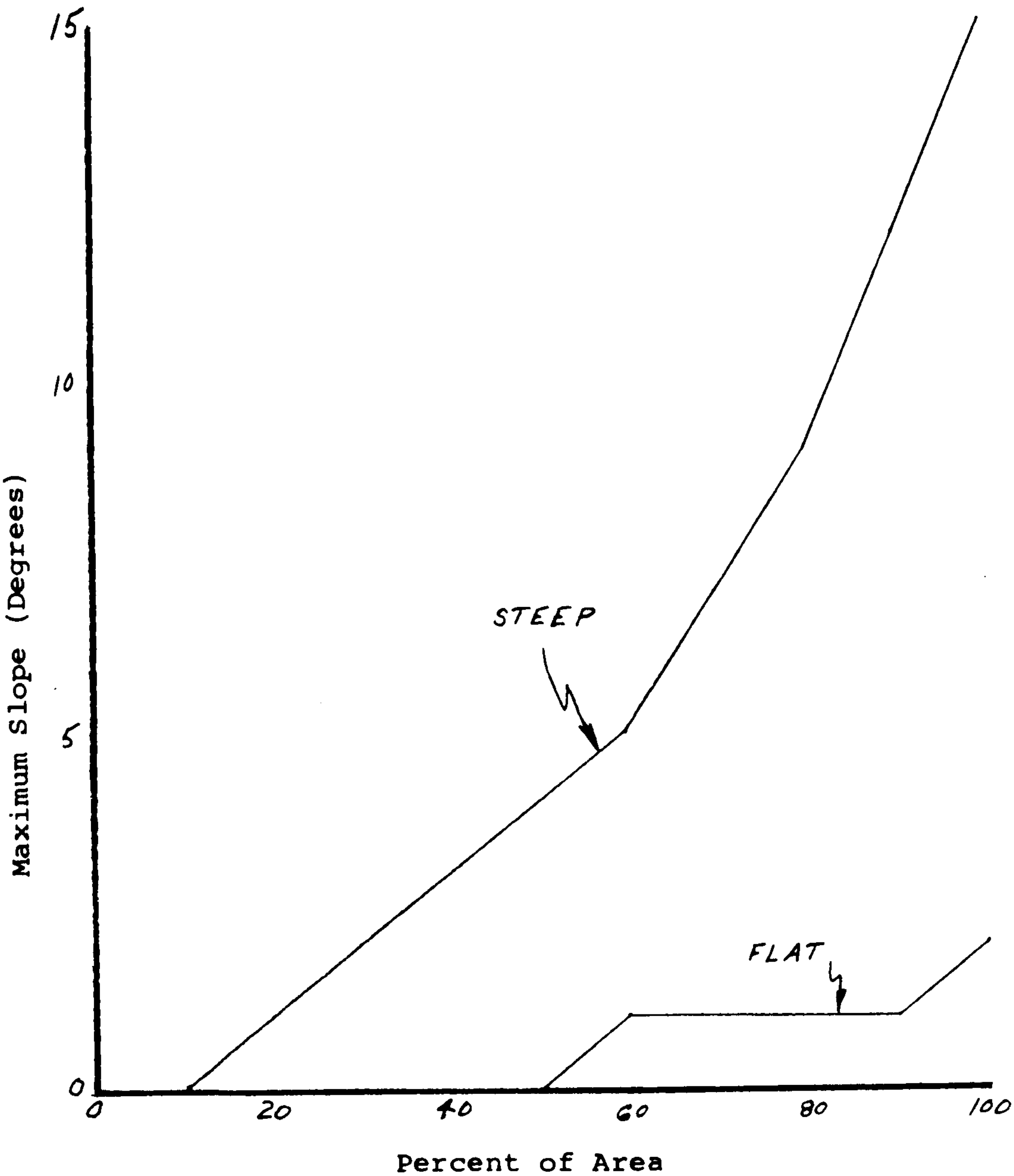

Figure 3-6 Definition of Slope Models

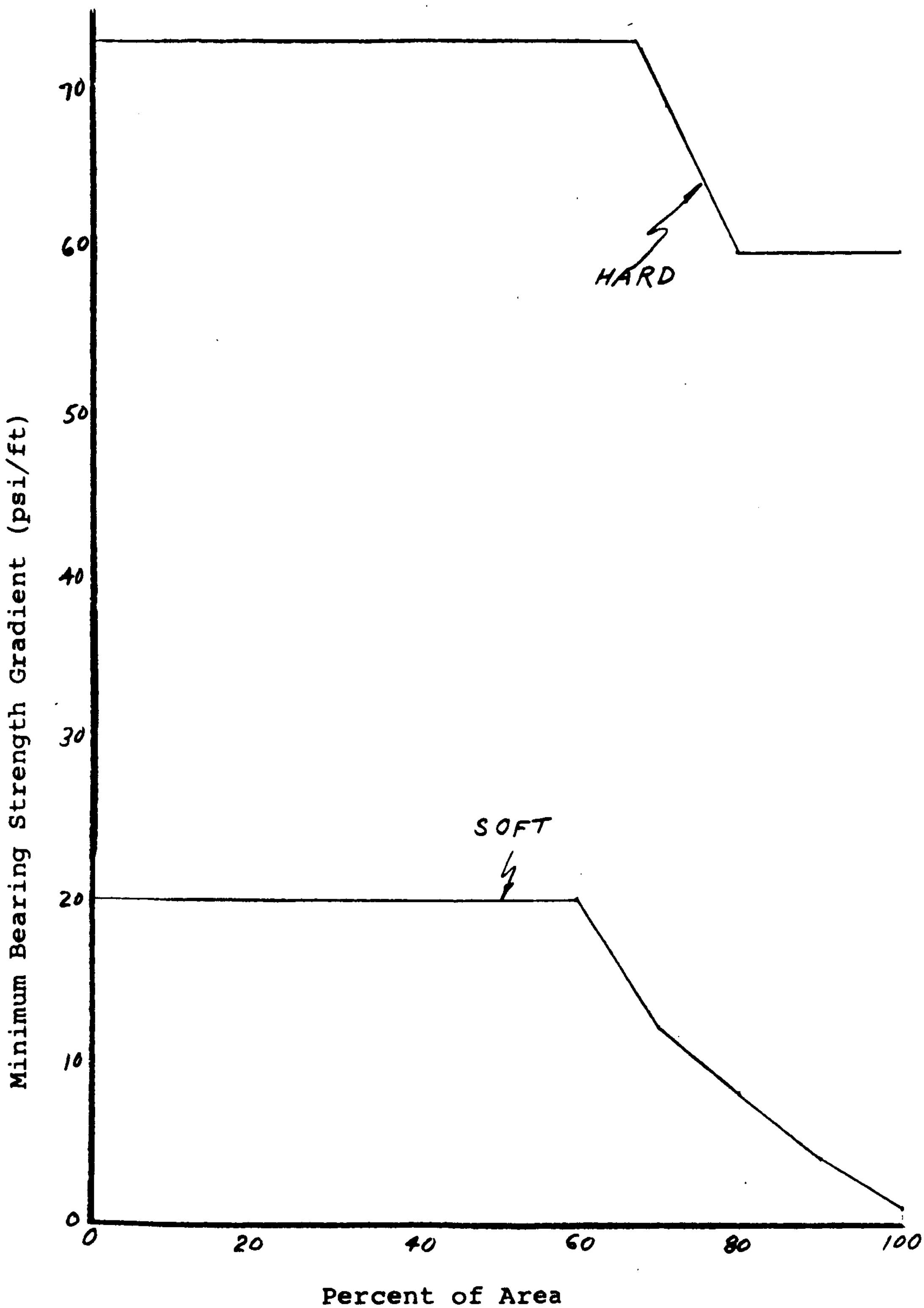

Figure 3-7 Definition of Bearing Strength Models

Model	Description	Will Show Effects Of
1	Smooth, Flat, Hard	________
2	ROUGH, Flat, Hard	Irregularities
3	Smooth, STEEP, Hard	Slopes
4	Smooth, Flat, SOFT	Bearing Strength

Models 5, 6, and 7 are generated by changing two particulars of model 1 for each. Thus,

Model	Description	Will Show Effects Of
1	Smooth, Flat, Hard	________
5	ROUGH, STEEP, hard	Irregularities and Slopes
6	ROUGH, Flat, SOFT	Irregularities and Bearing Strength
7	Smooth, STEEP, SOFT	Slopes and Bearing Strength.

Model 8, the most adverse, is the combination of all three adverse conditions. With these definitions and the definitions of each particular as shown in Figures 3-5, 3-6 and 3-7, the set of eight models satisfies requirement No. 3. Table 3-1 summarizes the eight models.

These models do not incorporate the concept of "effective" hazards as defined in Appendix A of EPD-98. To do this requires relating the physical position of, for example, soft areas relative to irregularities. This is beyond the present simulation scope, but could be incorporated in the future.

Referring now to Figure 3-4, it is seen that the surface models are employed in both the point survey and the interpoint travel routines.

TABLE 3-1

SURFACE MODEL SUMMARY

Model Number	Irregularities	Slopes	Bearing Strength
1	Smooth	Flat	Hard
2	ROUGH	Flat	Hard
3	Smooth	STEEP	Hard
4	Smooth	Flat	SOFT
5	ROUGH	STEEP	Hard
6	ROUGH	Flat	SOFT
7	Smooth	STEEP	SOFT
8	ROUGH	STEEP	SOFT

Note: Bold face type indicates adverse condition.

There is some argument that the use of the same model for both events is not realistic. For example, the existence of 100-cm irregularities in an area chosen for a point survey is unlikely, since major obstacles could be spotted with pictures before the survey gets underway. A location, before being considered as a possible point, would therefore contain fewer large obstacles. Thus, the "rough" definition should be somewhat less rugged for the point survey. This detail has not been incorporated in the present simulation; the model is identical for both events.

In the point survey, the percent of the surface which is unacceptable to LEM is determined by comparing the LEM requirements on irregularities, slopes, and bearing strength to those found in the particular model in use. Expressing this percentage as a probability that the point area is good or bad then permits a statistical test to determine if the point in question is good. Note that for fixed LEM requirements and a given surface model the probability of finding an acceptable point is a constant. Thus, over a large number of runs, a fixed fraction will be scored as good with the remainder being bad. If a good point is scored, the simulation goes on to a standard time and distance increment. However, if a bad point results, the question of how many tries to make arises. At present, four tries are made before the point location is abandoned.

The surface model is also required in the interpoint travel subroutine. By comparing SLRV mobility capabilities with the surface model, the percent of any travel leg which is impassable is determined. This fraction is then used in a detour equation to compute the time and distance penalties required to avoid the impassable area. Note again that for fixed SLRV capabilities and a given model, the percent of impassable surface will be a constant. By changing the SLRV capabilities in any particular, the effect of design changes on the probability of success is available from the simulation. It must be remembered, however, that results are a direct function of the surface model used and should be viewed in the light of this limitation.

LEM Landing Requirements

The LEM landing requirements input consists of three constants which indicate the LEM landing requirements as set forth in Appendix A of EPD-98, Revision 1, combined with the measurement capabilities of the SLRV system. Appendix A requires that all points containing 50-cm irregularities be rejected. However, in this simulation, all points containing irregularities greater than 18 cm are rejected to ensure that all effective slopes (slope plus irregularities) are less than 12°. Similarly, all true slopes of 9° are rejected to guarantee that no effective slopes combined with irregularities exceed 12°, the LEM requirement. All bearing strength gradients below 12 psi/ft are also cause for rejection.

The LEM capability is therefore a strong factor in determining SLRV success in that lower LEM landing capability means more searching by SLRV. Another significant consideration is the increase in LEM landing probability afforded by SLRV over a blind landing by LEM. For a "good" moon, the SLRV would contribute much less than for a "bad" moon. This consideration is beyond the scope of the evaluation.

Time, Distance Relationships—Point Survey

To complete the point survey subroutine after determining whether a good or bad point has been scored, the time and distance required for the survey is computed and entered as operating time. This computation differs somewhat depending upon whether a good point is found on the first try or whether several tries (searching) are required.

For a complete point survey, the computations for time and distance increments, respectively, are

$$\Delta T = T_D (1 + L_{max} K_8)$$
$$\Delta D = D_D (1 + L_{max} K_8) \qquad (3\text{-}1)$$

where

T_D = time to survey a good point

D_D = distance accrued in surveying a good point

L_{max} = number of false starts before finding the good point

K_8 = Average fraction of total survey completed before point is rejected.

Equation (3-1) therefore consists of adding a nominal time and distance for the good point plus an allowance for any false starts required before the good one was found. The time T_D includes the following items:

		Time (minutes)
1.	Decision making	558
2.	TV transmission	118
3.	TV slew	124

		Time (minutes)
4.	Antenna slew	10
5.	Travel	173
6.	Penetrometer operation	96
	Total	1079

The distance D_D is a function of the pattern used in the survey and is the total of all distances shown in Figure 3-1(a). The number of false starts to be allowed is determined from strategy analysis and is presently set at four.

The constant K_8 is estimated to be 0.4 based on examination of the following reasons for abandoning surveys:

1. Irregularities too large for LEM
2. Slopes too steep for a LEM landing
3. Soil too soft for a LEM landing.

There is an equal probability of rejection for the first two reasons anywhere within the point; hence, a bad point would be rejected at the half-way mark (on the average). A fairly good indication of the soil characteristics (reason 3) will be obtained before the first half of the point survey is completed, as it is quite unlikely that there will be abrupt changes in the soil bearing strength. Thus, finding the first half acceptable will provide high confidence that the entire point is acceptable. On the average, point rejection for inadequate bearing strength is expected to occur when 25% of the point survey is completed. Taking the average of the completed portion for the three cases results in a value of

$$K_8 = \frac{0.5 + 0.5 + 0.25}{3} \approx 0.4.$$

Therefore, a factor of 40% is used as the average completed portion for each rejected point.

Marking Schedule

The marking schedule for the fixed strategy input consists only of a record of the points where marking is to be accomplished. A typical schedule calls for marking at points 4, 7, and 10. When marking is required, a nominal six minutes is added to operating time. No distance increment is entered, since the marking occurs at the survey points.

Reliability Data

The reliability input presently used is the reliability vs time curve shown as Figure 3-8. The details behind this curve are given in Volume IV and are not repeated here. The use of this curve in determining whether a failure has occurred should be explained. Figure 3-8 indicates only the probability of a failure as a function of actual time. If reliability is initially checked at point (1), corresponding to completion of point #1 and time adjustment #1, the probability of reliability is R_1. Thus, to test whether a failure has actually occurred in the mission at this point, the probability of successful operation is R_1. If point (2) then corresponds to completion of point survey #2, time adjustment #2, the reliability test is not made with a probability of success (no failure) of R_2, but rather is an event with probability of success R_2/R_1. As the time t_2 moves towards t_1, the ratio R_2/R_1 approaches unity.

Operational Constraints

Figure 3-9 shows the following constraints on operating time:

1. A 24-hour period immediately after dawn in which system warm-up is completed and in which operation is impractical because of poor visibility

2. Periods when the DSIF is unavailable

3. A short period centered about high noon when sun sensor limitations are present

4. A 24-hour period immediately preceding nightfal when visibility makes operation impractical

5. Lunar night.

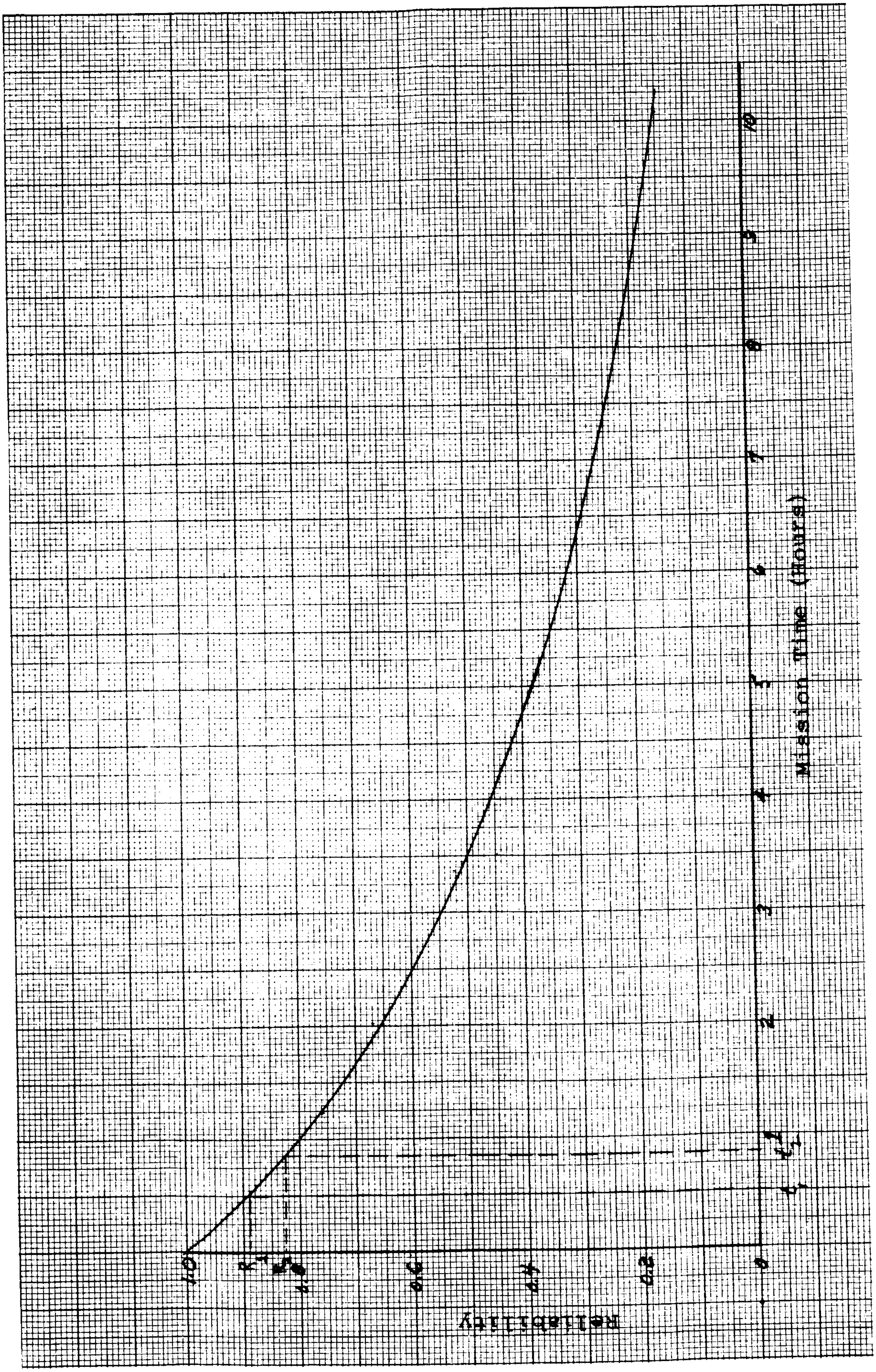

Figure 3-8 Reliability Input

V

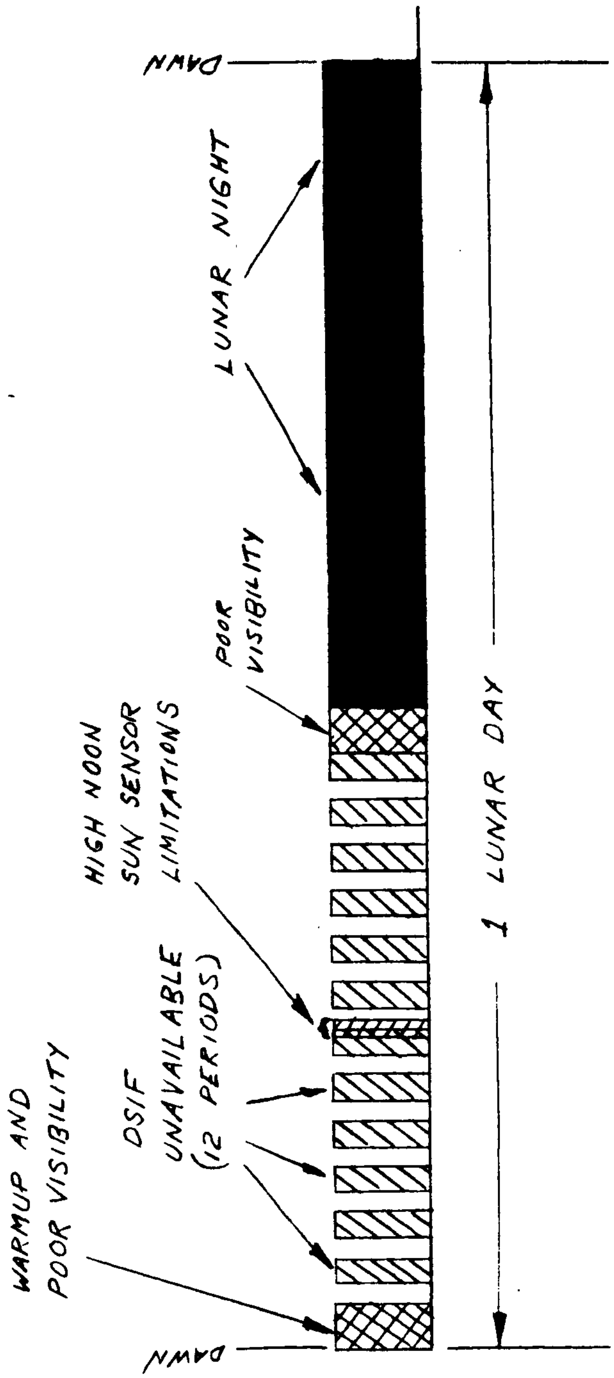

Figure 3-9 Operational Constraints

These constraints are inserted to convert "operating time" to "actual time" which increases the mission time to include these standby periods.

Roving Pattern Definition

Definition of the roving pattern was the result of mission and system studies and was shown in Figure 3-1(a). As an input to the present simulation, the pattern is a listing of the point sequence to be followed together with the interpoint distance.

SLRV Terrain Capabilities

The SLRV terrain traversing capabilities required are three with current values as shown:

1. Maximum irregularity - 30 cm

2. Maximum slope - 15°

3. Minimum bearing strength gradient - 1.0 psi/ft.

During the interpoint travel subroutine, these capabilities are compared with the surface models to determine the percentage of the distance to the next point which is impassable.

Time, Distance Relationships—Interpoint Travel

The final step in the interpoint travel routine is the computation of the time and distance required to travel to the destination point. In the ideal case, with no hazard or impassable terrain, the distance travelled would be just the straight-line interpoint distance, and the time required just the straight-line distance divided by the average rate of travel. The rate of travel includes such effects as: (1) time for actual travel, (2) data collection, (3) transmission, and (4) decisions. These items include everything in the point survey time calculations except the penetrometer.

When impassable areas are encountered, the SLRV must detour. The amount of this detour depends upon the severity of the model and is discussed later. The computation of the interpoint travel distance and time are made as follows

$$\Delta D = D_i (1 + \delta_F F)$$
$$\Delta T = \frac{\Delta D}{V_{avg}} \qquad (3\text{-}2)$$

where

D_i = straight-line distance of the ith leg of the pattern

δ_F = detour distance deviate $(0 \leq \delta_F \leq 2)$

F = detour distance factor

V_{avg} = average interpoint rate of travel.

The factor F is the mean additional fraction of the straight-line distance which is required for detouring around impassable areas. The deviate, δ_F, provides for the distribution about this mean. Figure 3-10 shows the magnitude of detour factor F as a function of the percentage of a travel distance which is impassable. The dotted line indicates values obtained by a graphical analysis (experimental), while the solid line is the equation

$$F = \frac{0.559A}{(1-A)^{1.4}} \qquad (3\text{-}3)$$

where

A = fraction of area which is impassable.

This function, being quite close to the experimental curve, is used in the simulation. Thus Equations (3-2) and (3-3) are employed to compute the interpoint time and distance. These computations complete the simulation cycle.

The method of generating the experimental curve for detour factor F will now be discussed. Three basic requirements were established which must be met by the approach:

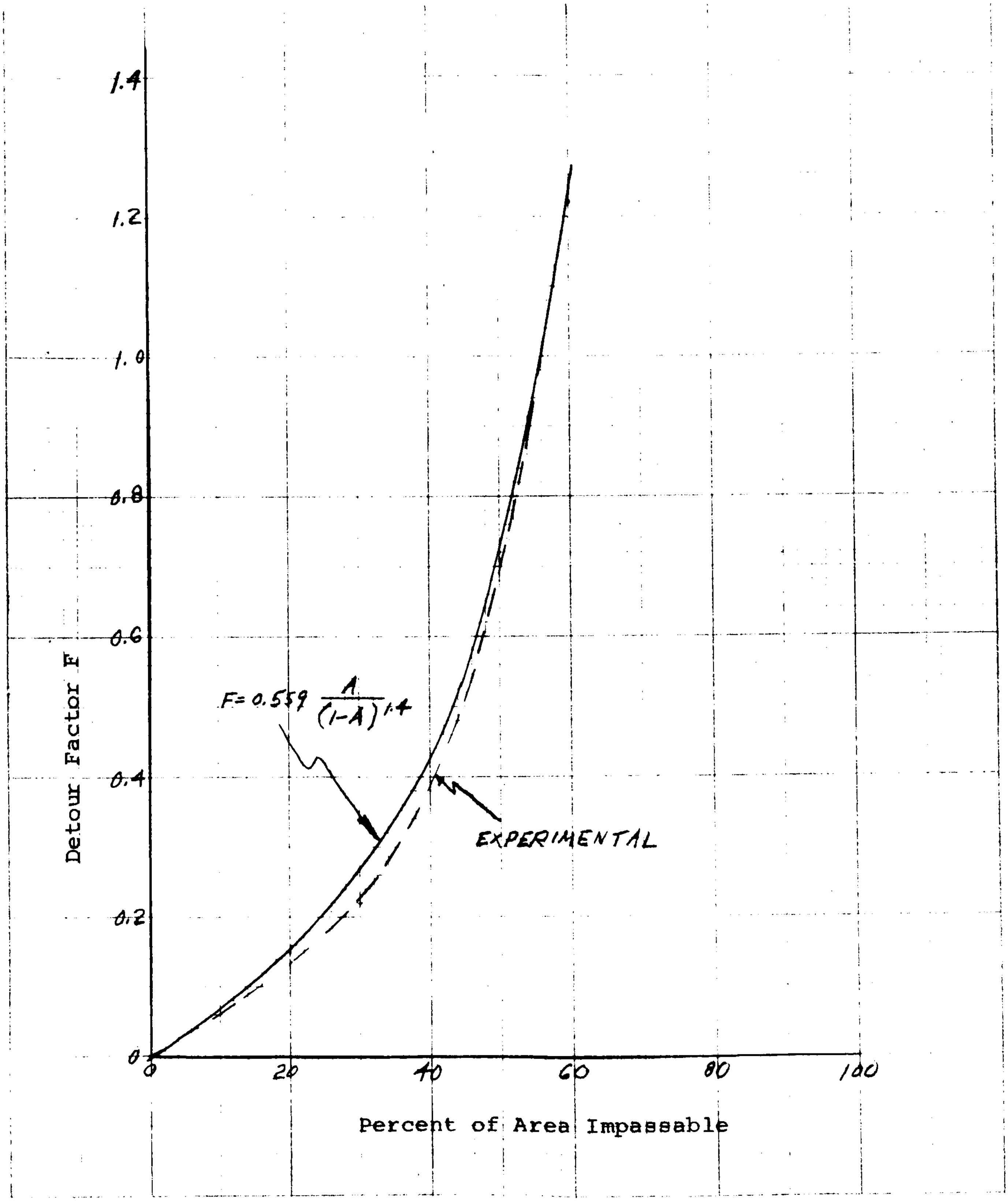

Figure 3-10 Detour Factor, F

1. The statistical nature of the detour situation should be preserved. Thus any simple, constant penalty is outlawed.

2. Any relationship derived should be traceable to a definite surface model.

3. The surface model definition should permit separate investigators to generate the same F-curve independently.

The starting point in the approach is the percent of the surface which is impassable. In the simulation, this represents irregularities with dimensions exceeding the LRV capability. Since it was assumed that the size and makeup (e. g., whether in chains or not) of obstacles was dominant in determining the detour magnitude, random maps were generated on the basis of:

1. Obstacle size - hereafter termed "kernel" size, since it may represent other than obstacles

2. Percent of total map area which is impassable; i. e., the portion which contains kernels.

The map is generated by using a square grid with each square representing one kernel. From a random number selection based on the percentage bad (and therefore the probability that any square is a kernel), the complete grid is covered one square at a time, determining whether each square is a kernel or not. A simple check on the results is made by counting the squares scored as kernels and computing the actual percentage of the map which is impassable.

Illustrative maps are shown in Figure 3-11 and 3-12 for 20% bad and 50% bad, respectively. Note that the formation of chains (akin to crevices, ridges, etc.) is automatic. Furthermore, as the percentage bad increases, detour direction becomes more difficult to choose, and blind alleys also occur. From the basic information of kernel size and percentage bad, one can generate any number of maps. All of these are different, but all will have the same statistical properties and are therefore "identical" as far as detour computations are concerned.

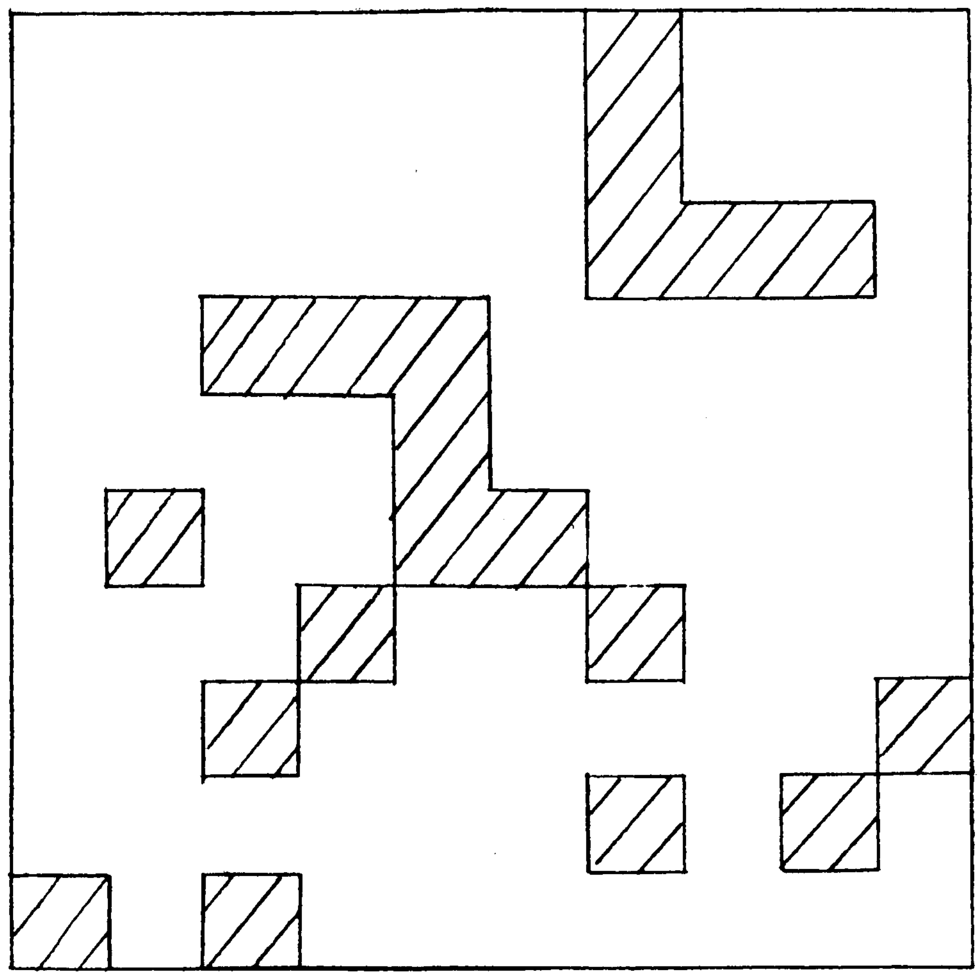

Figure 3-11 Random Terrain Map, 20% Bad

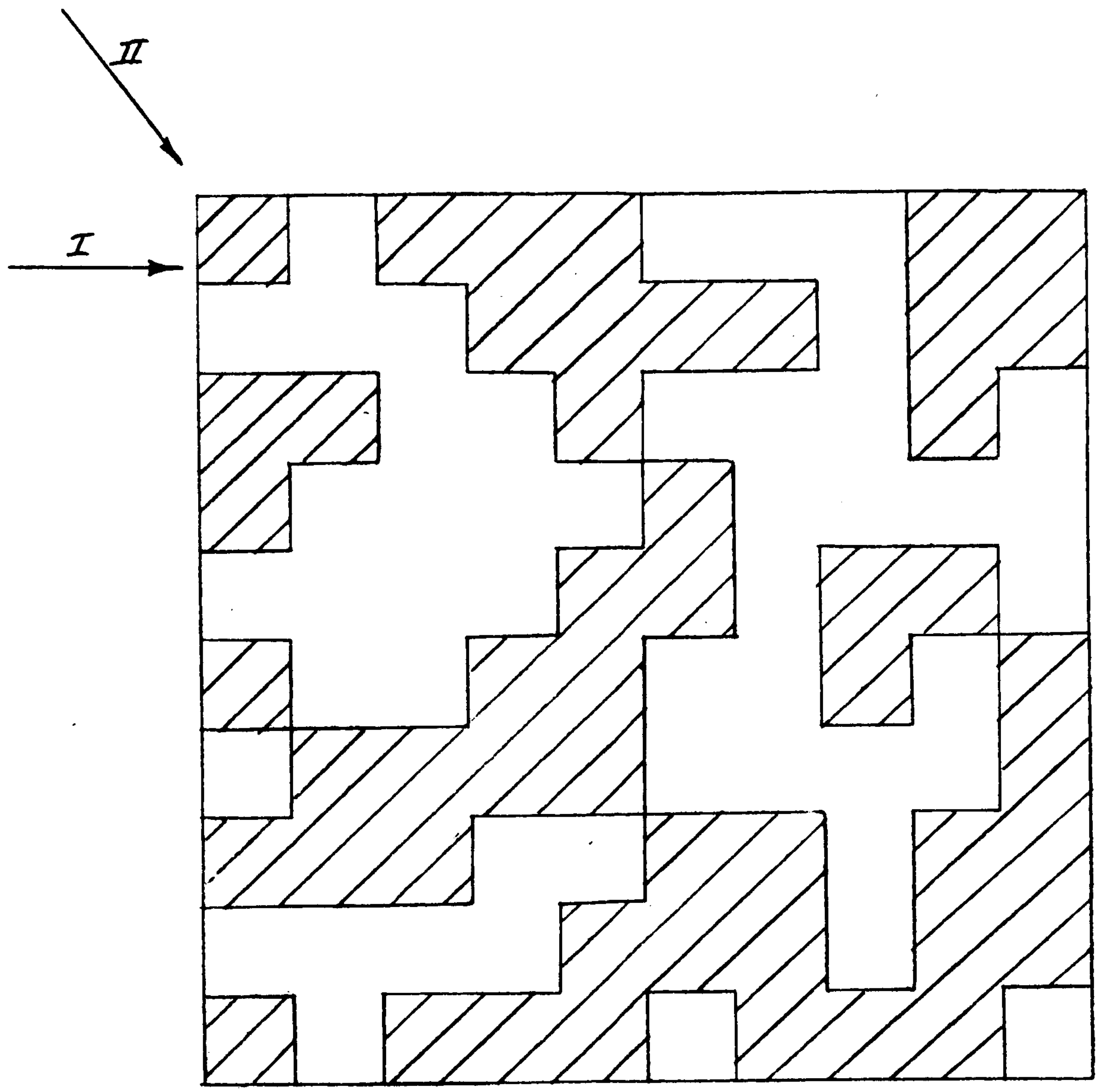

Figure 3-12 Random Terrain Map, 50% Bad

After deriving several maps of various percentages bad, one point on the F-curve can be determined for each map. This was done by placing an overlay of the 19-point roving pattern on each map and tracing feasible interpoint travel routes for the mission, detouring around kernels as required. The amount of detour was tabulated and the mean computed for each map. The deviate Δ_F represents the distribution about this mean.

As a part of this study, the effect of kernel size on detour distances was also investigated. The same maps were used, but the pattern overlay was varied in size, giving the effect of a different kernel size. The "20% bad" map was checked with the following results:

Map Definition		
% bad	Kernel Size	Value for F
20	17.5 meters	0.15
20	88	0.20
20	176	0.14.

Little differences were found in the F value as kernel size varied. However, more work must be done to substantiate this conclusion. Kernel shape was also considered, the square and circle receiving most attention. The circle is superior to the square in one respect; the detour around a circle is independent of the direction of approach for a given offset from the center. This is not true for the square. To compensate somewhat in this work for this fault of the square, an equal number of cases were taken for both directions I & II shown in Figure 3-12.

Generating maps using circular kernels was generally more time-consuming and evaluation more difficult than when using squares. The squares, moreover, can quite easily be made to represent any shape of hazard simply by making the kernel size small enough. Also, when circles are used, there is quite a bit of area which must be accounted for between adjacent circles.

Referring back to the three requirements in the opening paragraph, it is seen that requirement No. 1 is satisfied since the detour distance is represented by a mean F depending on the percentage of the area which is bad. The distribution about the mean is represented by the random deviate Δ_F. Also, any F-curve such as Figure 3-10 is directly related to a definite surface model defined by (a) percentage bad and (b) kernel size. Thus the second requirement is met. Finally, if an investigator starts with a given percentage and kernel size, he can use a random number table to generate a map, differing in detail from that of another investigator working independently, but identical in statistical properties; therefore it will result in the same F-curve. Thus the third requirement is met.

It should be noted that the F-curve shown in Figure 3-10 represents a minimum value, because the ready-made map was partially visible to the "SLRV operator". The detour distances would be longer when operating more blindly, e.g., like a mouse in a maze.

3.1.2.3 Failures

The treatment of vehicle failures in the simulation differs, depending on whether the failures under investigation are catastrophic or partial.

Catastrophic Failures

When a failure is catastrophic, the approach is essentially the one outlined in Section 3.1.3.1. A single reliability vs time curve is used as the basis for reliability testing following each point survey and time adjustment. If a failure has not occurred, the simulation merely proceeds. If a failure has occurred, the mission is terminated, and the results are tabulated.

Partial Failures

Two approaches are currently being used to evaluate the effects of partial failures. In the first approach, a partial failure is inserted at the beginning of the mission. The basic system reliability curve for catastrophic failure is also inserted. The decrease in probability of success due to the partial failure is then evaluated. By studying many partial failures in this manner, the criticality of individual failures may be determined. To insert the partial failure, the input data are changed, i.e., LRV capabilities in terrain negotiation, average speed, etc., are degraded. The major problem in evaluating partial failures is of course to determine the amount of degration brought about by a particular failure.

In the second approach, the system reliability curve is broken down into a number of curves, each representing the reliability of a subsystem or component of interest. There is a basic curve representing those items not broken out individually, this curve shows a higher reliability than the previous total system reliability curve. Each curve is tested during the reliability subroutine to determine if failures of the applicable items have occurred. When a failure occurs, appropriate changes are made in vehicle performance constants, and the mission is continued. Because of analysis limitations, the occurrence of two partial failures during a mission is treated as a catastrophic failure at the time of the second failure, and the mission is terminated.

3.1.2.4 Adaptive Mission

The adaptive mission is a variation of the basic mission in which the method of determining the interpoint travel and point survey time and distance is changed. This mission is intended to show the effects of an adaptive type of strategy in which learning plays a role. The 19 points are surveyed in the same order as for the basic mission, but the rate at which mission tasks are accomplished is made a function of how good or bad the lunar surface is found to be. The point survey time and distance are longer where the surface is marginally acceptable, and shorter where the surface is either obviously acceptable or not acceptable. Each point to be surveyed is placed in one of four categories, depending on the surface model:

1. Obviously good
2. Marginally good
3. Marginally bad
4. Obviously bad.

The time and distance incurred in surveying the point are then determined according to the category into which the point falls. The interpoint travel time is gradually decreased as more and more good area is found. When difficult terrain is encountered, the interpoint travel is again increased.

3.2 SIMULATION RESULTS

The results of the evaluation of the 100-lb SLRV will be discussed in the following order:

1. Probability of mission success as a function of the lunar surface conditions
2. Mission duration and distance as a function of the lunar surface conditions.
3. Probability of mission success as a function of SLRV reliability, considering both catastrophic and partial failures
4. Probability of mission success when SLRV tactics are made a function of the lunar surface conditions (adaptive mission).

3.2.1 Probability of Mission Success

The probability that the SLRV can successfully complete the mission of 19 points was found to be 0.30, using the basic (nonadaptive) mission and a combination of surface models. The probability of meeting partial mission objectives (less than 19 points) is shown in Figure 3-13. The impact of the lunar surface on the probability of success is seen from the three curves. Surface model No. 1 was used for the highest curve, and surface model No. 8 for the lowest curve; these surface models yielded the highest and lowest probability of success, respectively. This was to be expected since models 1 and 8 represent the most favorable and most adverse models, respectively. The middle curve shows the results from use of a composite of the surface models, where each surface model was used an equal number of times.

It is seen from Figure 3-13 that both the No. 8 and composite surface model curves "drop off" near the end of the mission, while the No. 1 surface model curve does not. The reason is that the mission was always ended after the 19th survey point, regardless of whether or not 19 good points had already been found. Only the good points were used in calculating the probability of success. Several bad points were found on most of the missions on surface model No. 8 which is the rough, steep, soft surface. However, very few bad points were found on the No. 1 surface model which is a smooth, flat, hard surface.

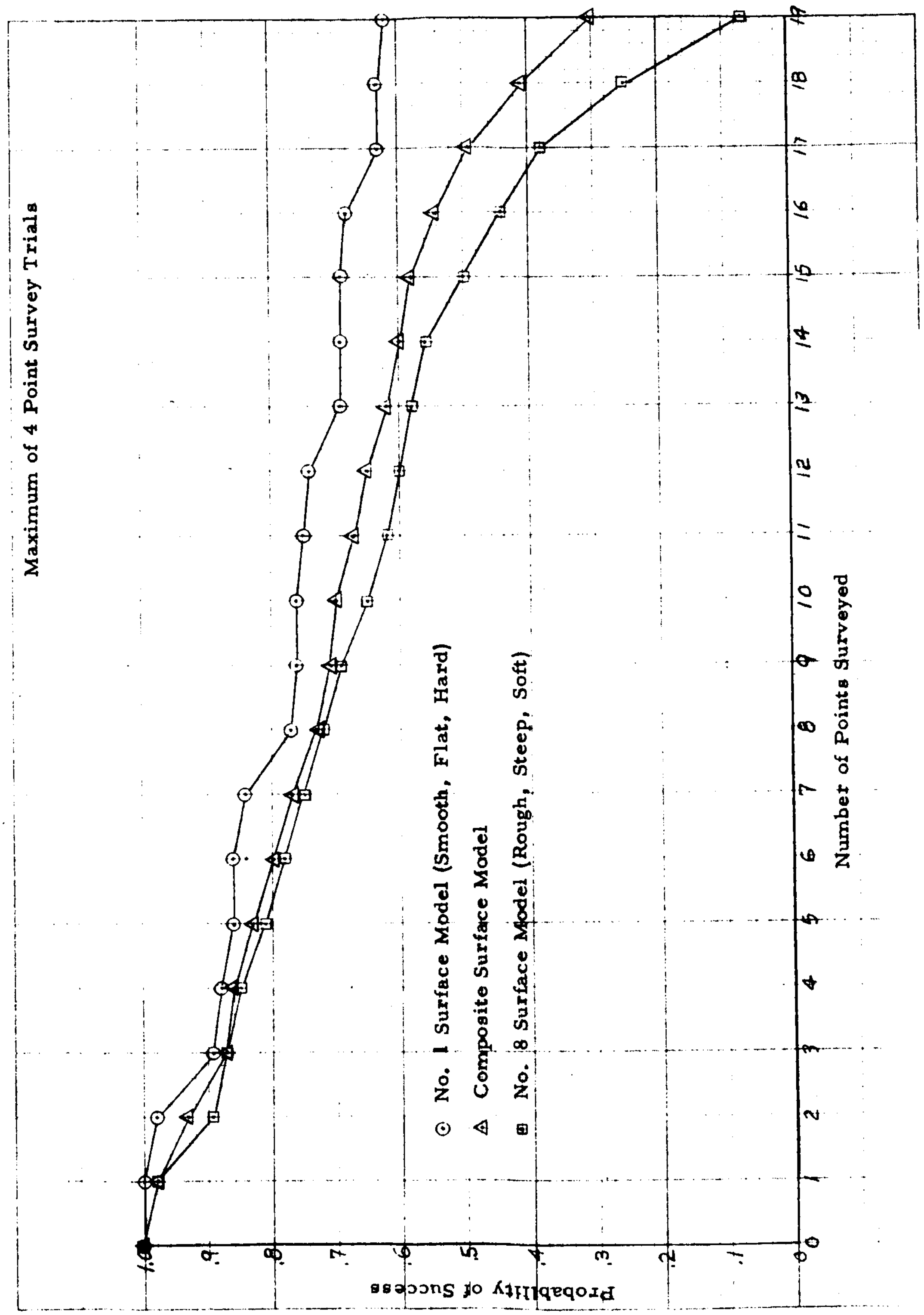

Figure 3-13 Effect of Surface Model on Probability of Success, Models 1 and 8 and Composite Model

The No. 1 surface model probability curve is not a smooth curve because of the decrease in reliability during the long lunar night. The No. 1 surface model is relatively easy to survey, so each mission takes about the same time. Lunar night falls after the survey of points 2, 7, 12, and 16 which accounts for the drop in the probability curve at these points. This effect is not as apparent on the other surface models, because the mission durations vary more and lunar nights do not occur after a definite point survey but are somewhat scattered.

The probability of success for completing the survey of a given number of points was found by calculating the percentage of the total number of missions in which at least the given number of good points was surveyed. It should be kept in mind that the probability of success as defined here includes neither the probability of successful deployment nor the possibility of human error in control of the mission.

The probability of success on surface models 2, 3, and 4 are shown in Figure 3-14. Each of these surface models is adverse in one of the three particulars used to describe the surface. The surface model No. 1 curve is included again for comparison. There is little difference between the No. 1 and No. 3 surface model curves. Slopes are steeper on surface model No. 3, but all the slopes are still traversable by SLRV and most of them are acceptable for LEM landing. The difference between the No. 1 and No. 2 surface model curves is much greater. Surface model 2 contains a considerable amount of area which is not acceptable for both SLRV traverse and LEM landing.

Results for surface models 5, 6, and 7 are shown in Figure 3-15. These surface models are adverse in two of the three particulars. Again, surface model No. 1 is included for comparison. Surface model No. 7 is not very much more difficult than surface model No. 1, even though both slopes and bearing strength are in the adverse category. This is simply because the SLRV can still traverse all of the area in the surface model. Surface models 5 and 6, however, are more difficult because irregularities are included in both models.

3.2.2 Mission Duration and Distance

The average mission duration and total distance traveled as a function of the surface model are shown in Figure 3-16. Mission durations

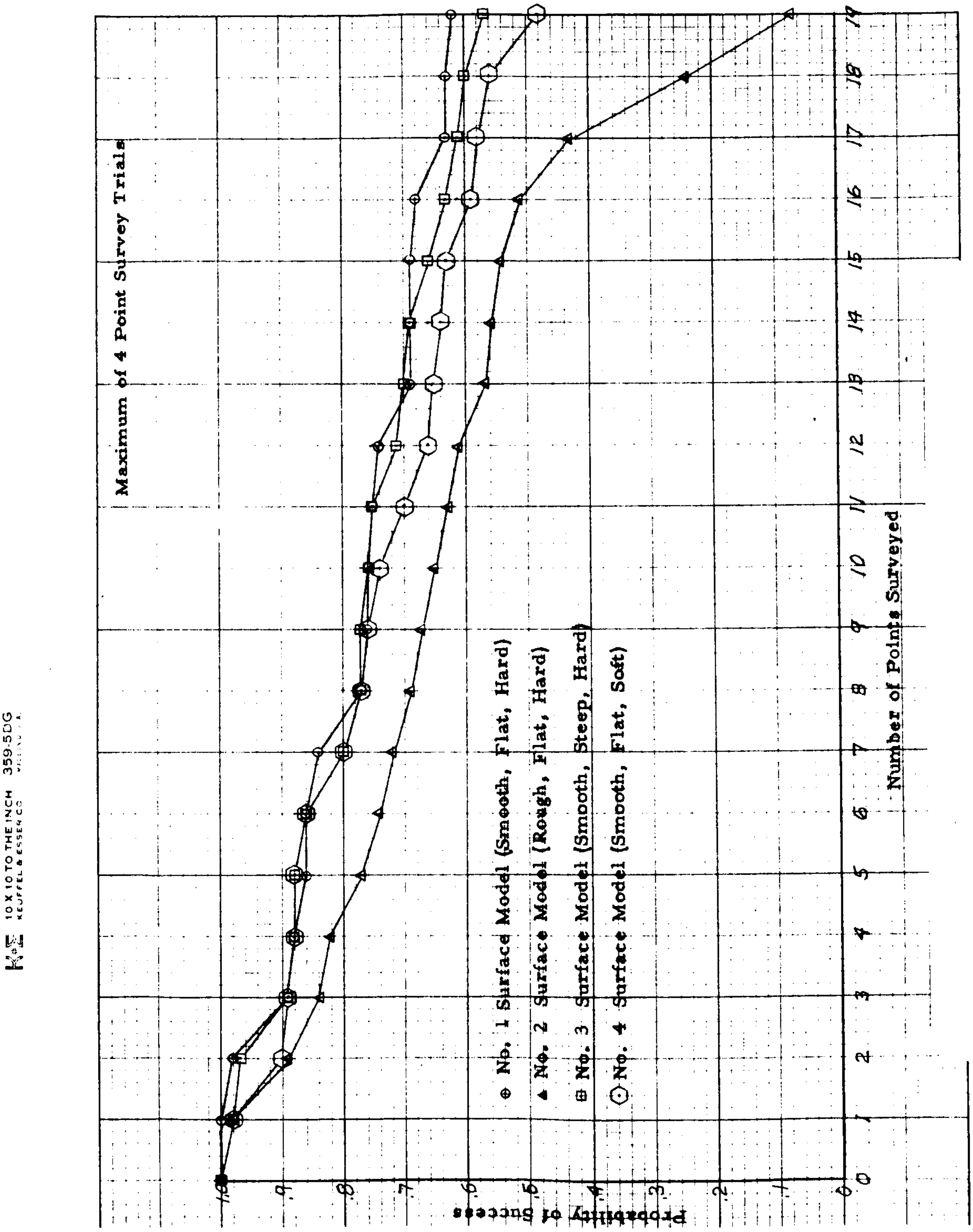

Figure 3-14 Effect of Surface Model on Probability of Success, Models 1, 2, 3, and 4

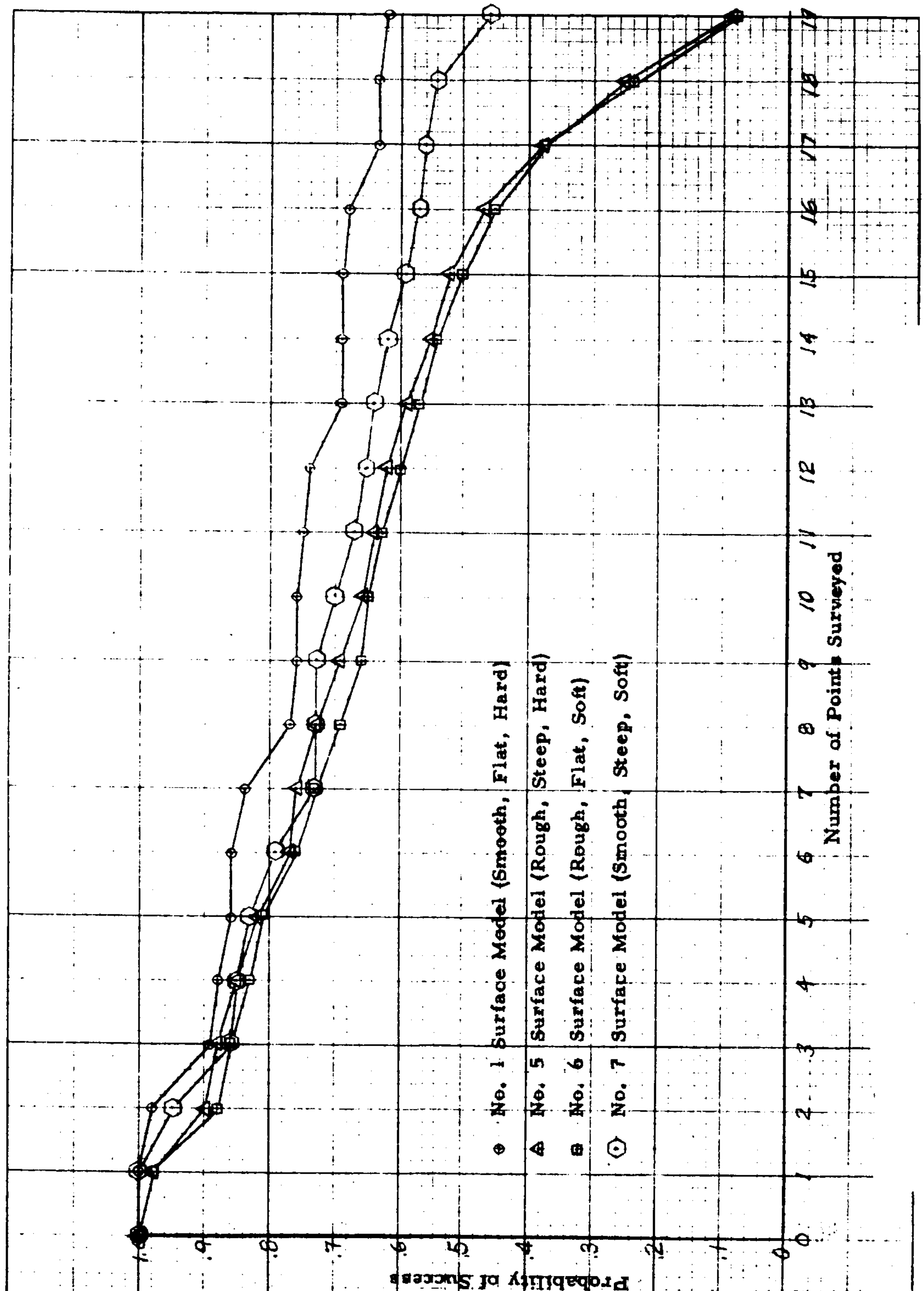

Figure 3-15 Effect of Surface Model on Probability of Success, Models 1, 5, 6, and 7

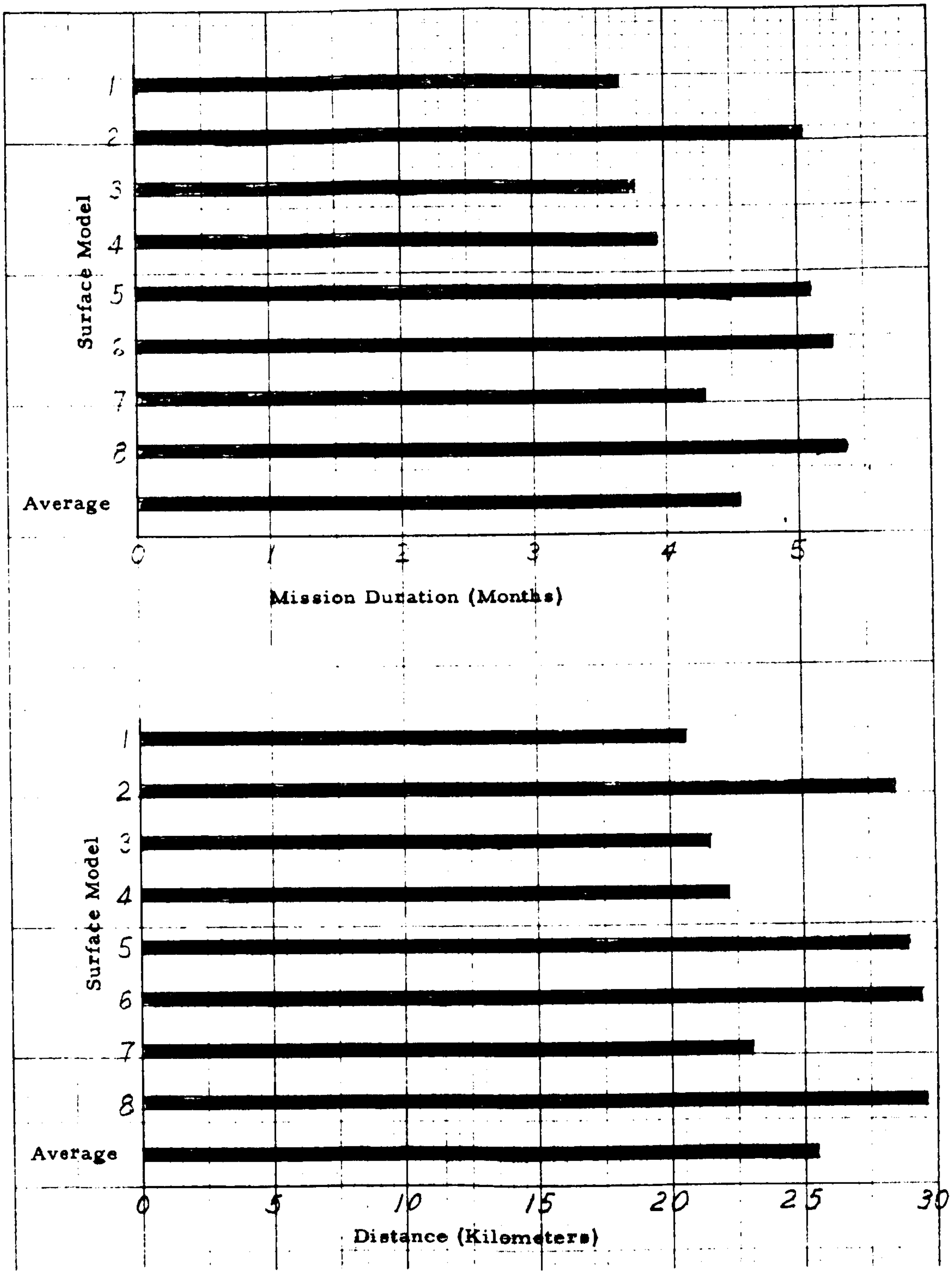

Figure 3-16 Effect of Surface Model on Mission Duration and Distance

and distances were averaged from those missions in which 19 good point surveys had been completed. It is seen that there is a strong relationship between mission duration and distance, which is to be expected. Mission duration varies from 3.67 months on surface model No. 1 to 5.35 months on surface model No. 8, with a mean of 4.56 months. Total distance traveled during the mission varies from 20.6 km on surface model No. 1 to 29.6 km on surface model No. 8, with a mean of 25.4 km. Times and distances are longest on models 2, 5, 6, and 8, all of which contain the more severe irregularities.

3.2.3 Reliability Effects

The probability of mission success was determined with two different reliability levels. The results are shown in Figure 3-17. Each surface model was used an equal number of times to make the results independent of the surface model. The lower curve represents the predicted SLRV reliability for the present design (see Volume IV). The upper curve is the same as that shown in Figure 3-13 and was plotted using the reliability data shown in Figure 3-8. These data are based on the anticipated reliability growth as the program progresses.

All of the above results were obtained under the assumption that all failures are catastrophic. This is obviously a rather conservative assumption, because many failures will merely cause a slowdown of the mission. Since determining the effect of each of the many possible partial failures is very complex, only six partial failures have so far been considered. The details of the approach in handling partial failure are contained in paragraph 2 under the heading "Partial Failure" in Section 3.1.2.3.

The probability of mission success with selected partial failures incorporated in the simulation is shown in Figure 3-18. The curve (Figure 3-13) in which all failures were considered catastrophic is shown again for comparison. It is seen that further operation after a partial failure gives a slight increase in the probability of mission success. The results shown were obtained using the composite surface model to make them independent of the surface model. The partial failures which were considered are as follows:

1. RF ranging

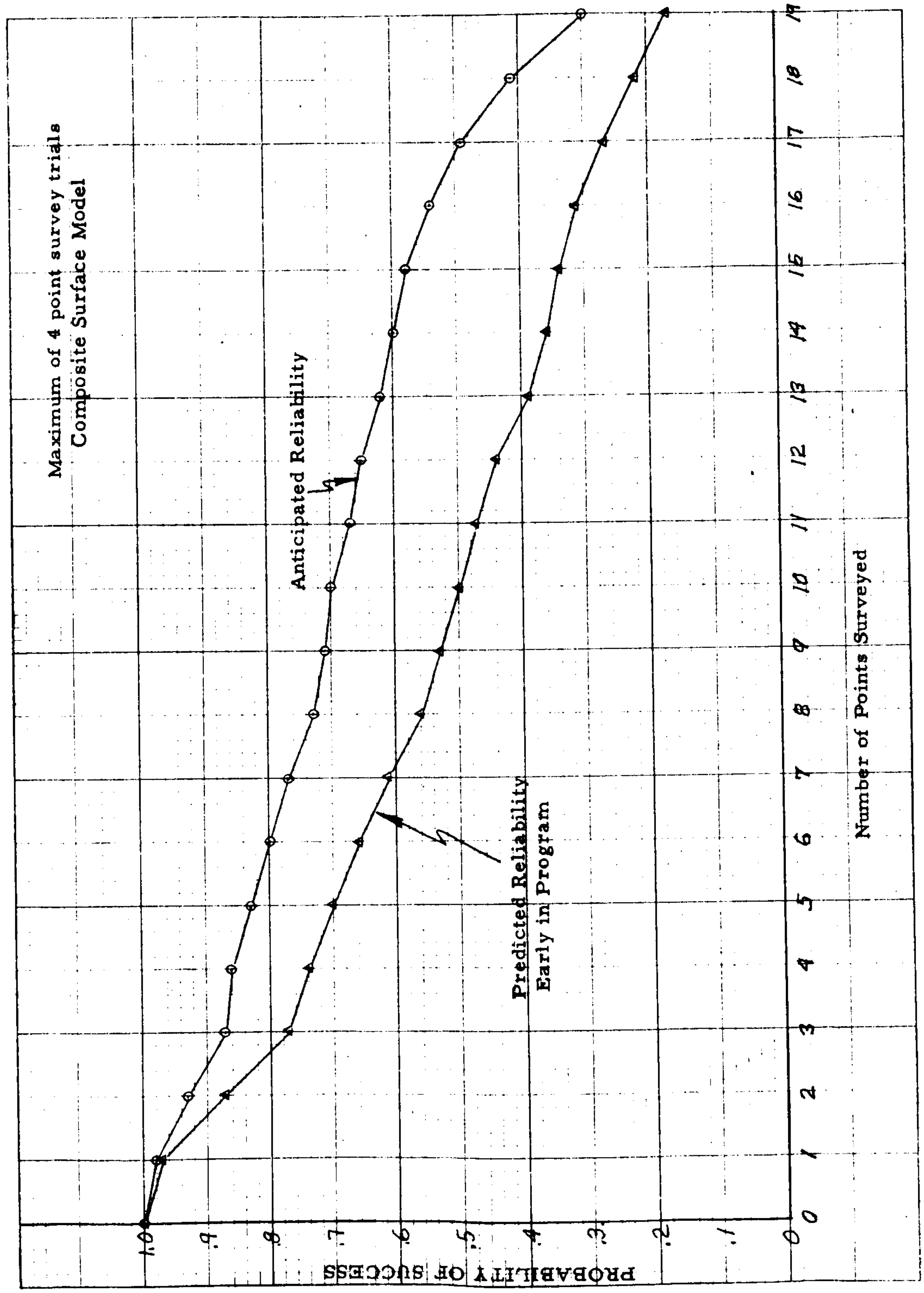

Figure 3-17 Effect of Reliability on Probability of Success

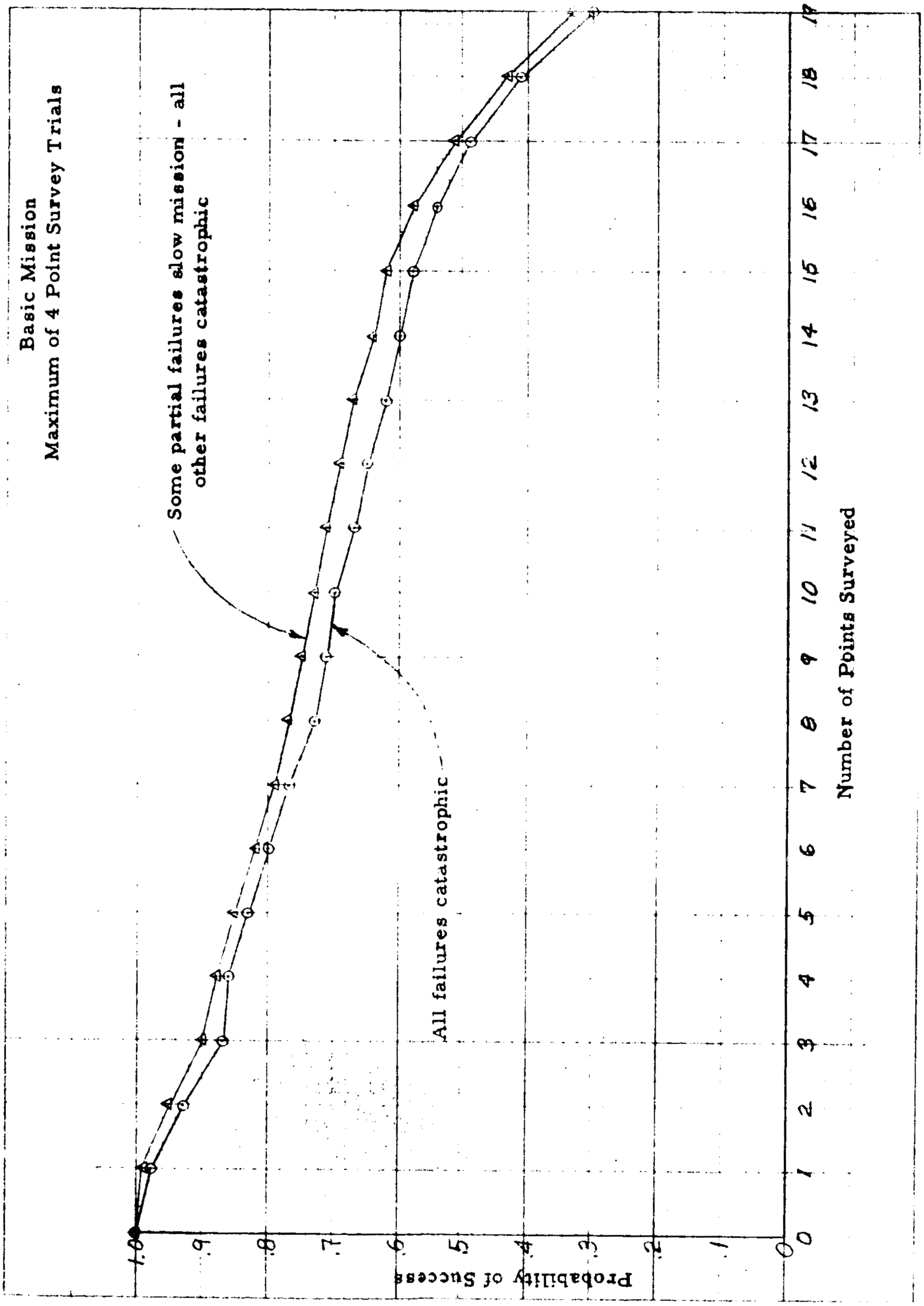

Figure 3-18 Effect of Partial Failures on Probability of Success

2. Traction drive motor (one track)

3. Directional antenna

4. TV azimuth pan

5. TV restricted to 10° field of view

6. TV, 50% loss of resolution.

To determine the effects of each of the above partial failures, the partial failures were inserted separately at the beginning of the mission as described under "Partial Failures" in Section 3.1.2.3. The results are shown in Figures 3-19, 3-20, and 3-21. Each figure includes for comparison the probability of success without the failure. Again, the composite surface model was used for all curves. A maximum of 10 point surveys were attempted in these missions before a point was abandoned (compared to only four tries in the basic mission). Thus, the number of bad points found was negligible, and the curves reflect only the reliability of the SLRV and are not influenced because of failure to find a good point on the 19-point survey attempts. The most critical partial failure of the six considered was failure of the RF ranging subsystem. The probability of completing the mission was 0.11 after the RF ranging failure. This compares to a probability of success of 0.42 with no partial failure.

3.2.4 Adaptive Mission

The probability of success for the adaptive mission is shown in Figure 3-22. These curves follow the same trend as those for the basic mission which were given in Figure 3-13. The spread between the curves for surface models 1 and 8 is also approximately the same. Because of the shorter mission times using the adaptive approach, only two lunar nights occurred during the total mission. The basic mission usually extended over three lunar nights. Lunar night, as explained for the basic mission, accounts for the sudden drops in the curve of No. 1 at points 4 and 14.

A comparison between the two approaches is shown in Figure 3-23, using the data of Figure 3-13 and 3-22 for the composite surface model. The probability of successfully verifying 19 points increased from 0.30 to

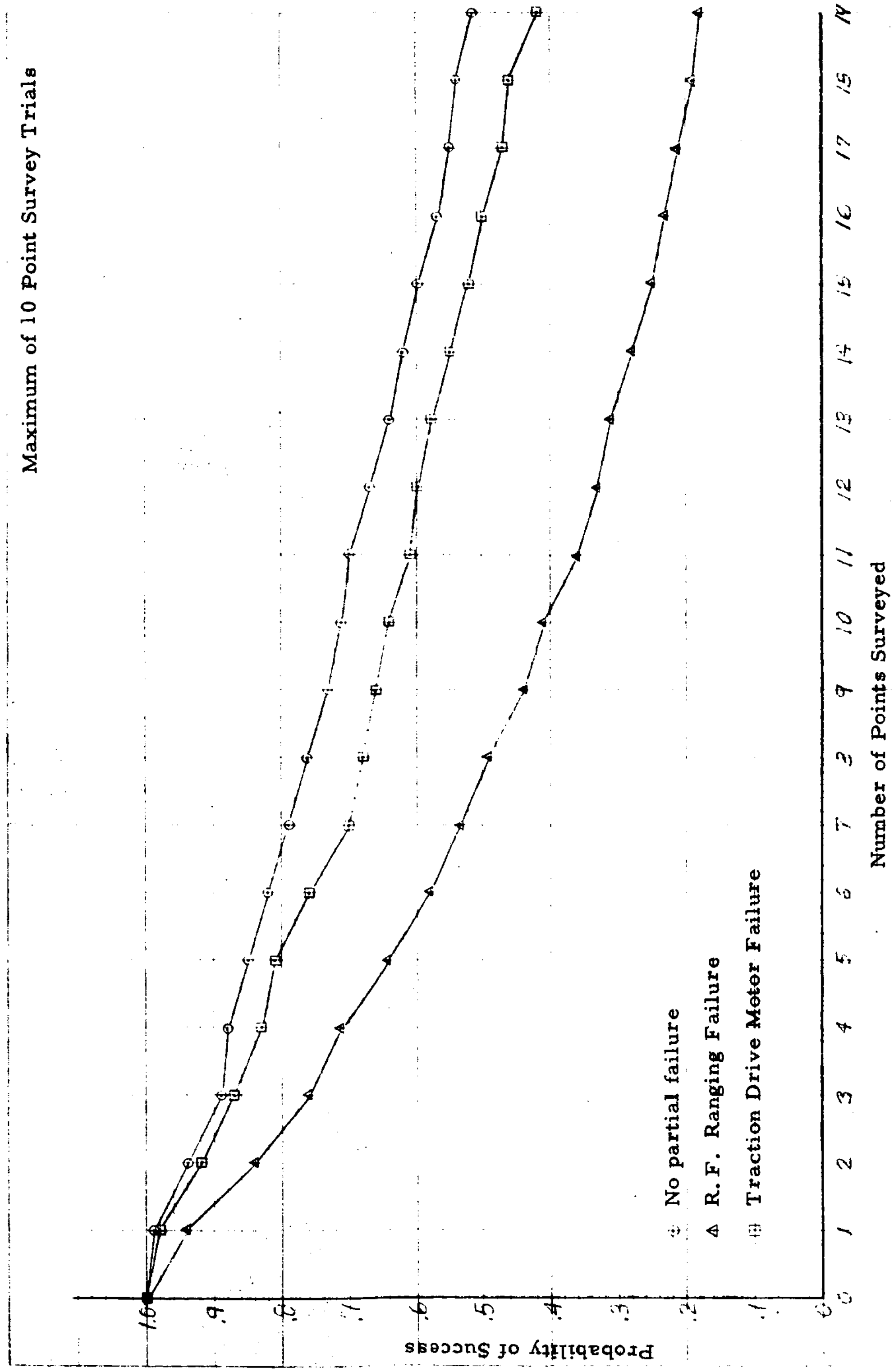

Figure 3-19 Effect of Partial Failure of RF Ranging and Traction Drive Mechanism at Start of Mission on Probability of Success

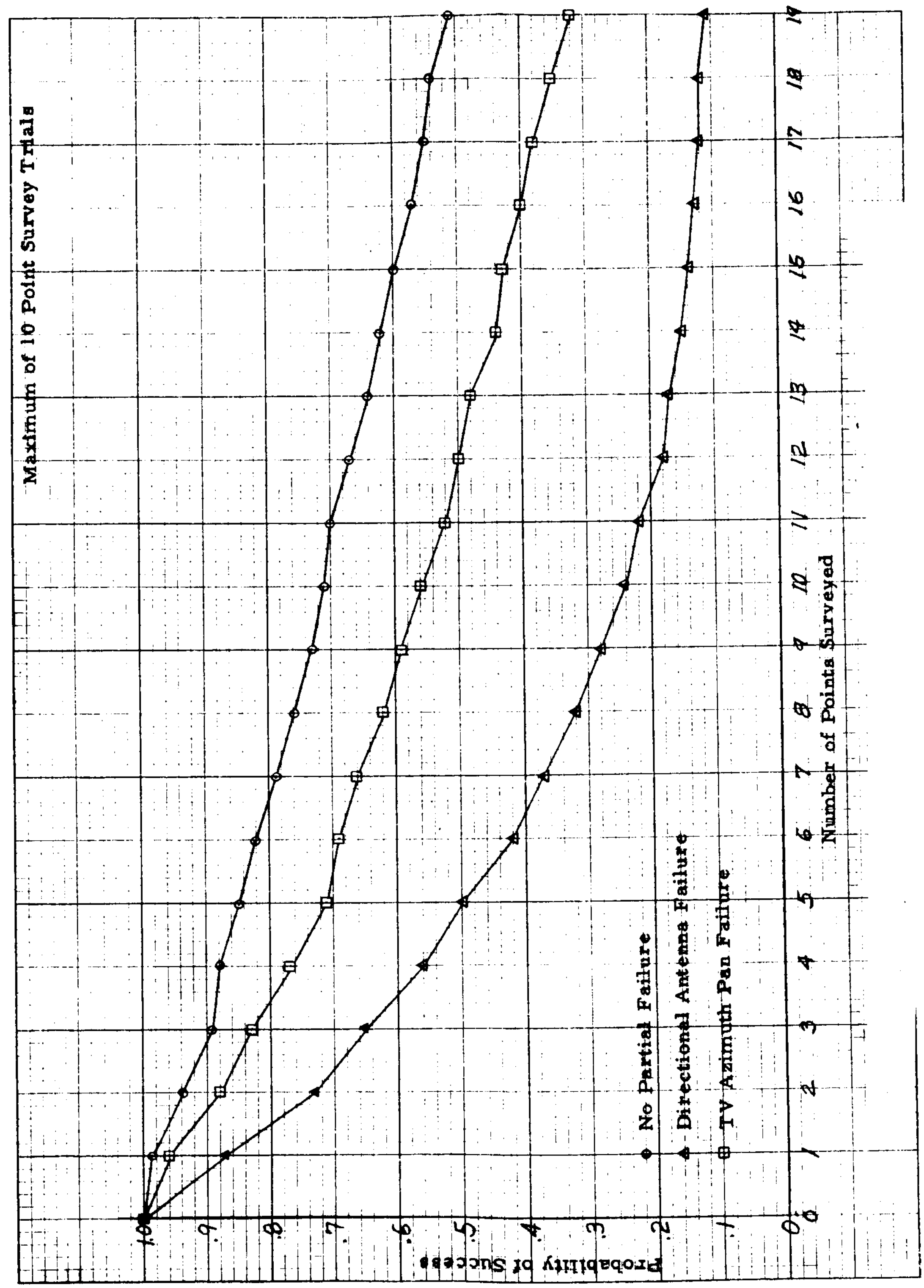

Figure 3-20 Effect of Partial Failure of Directional Antenna and TV Azimuth Pan at Start of Mission on Probability of Success

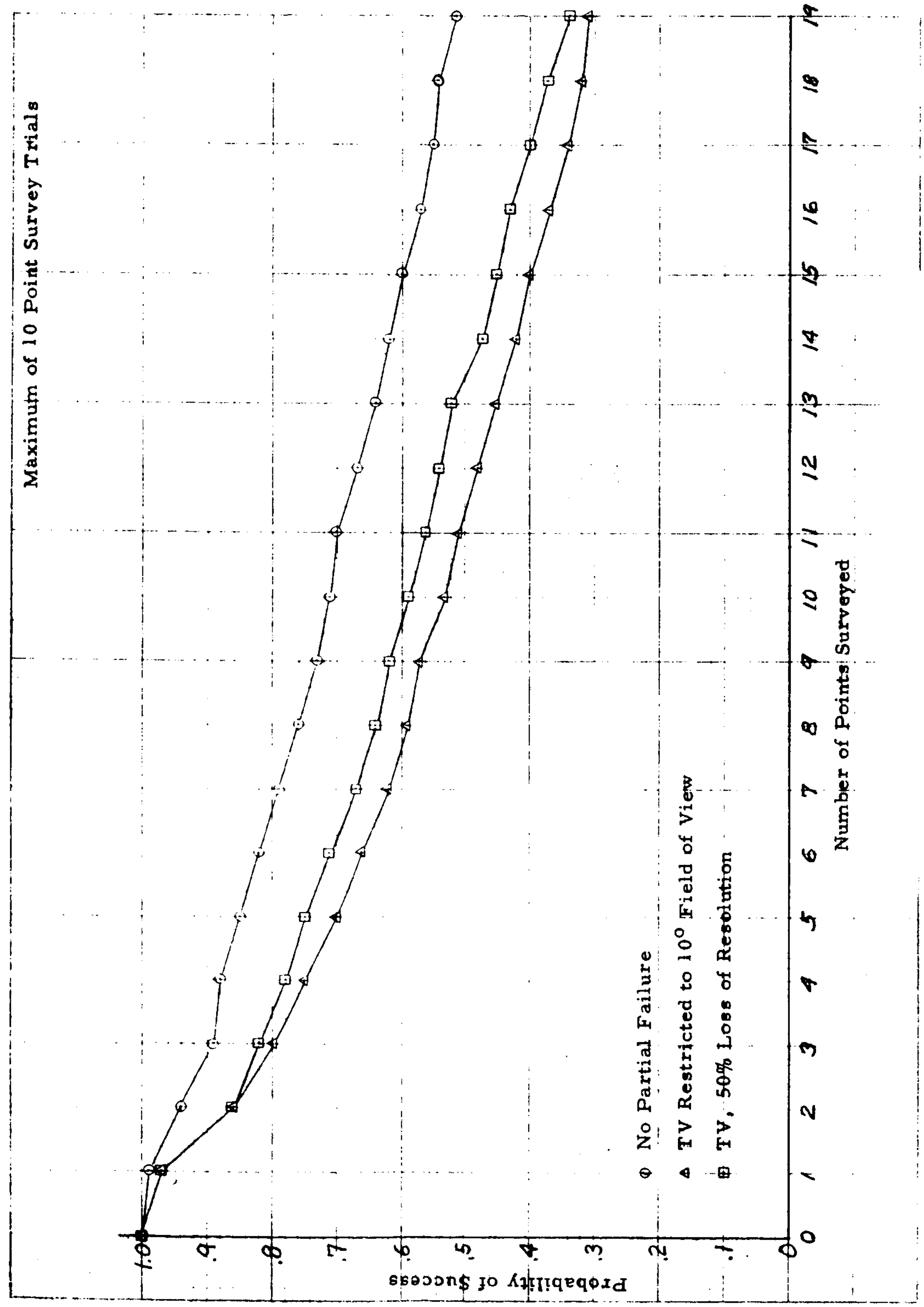

Figure 3-21 Effect of Partial Failure at Start of Mission on Probability of Success, TV Restricted to 10° Field of View, 50% Loss of Resolution

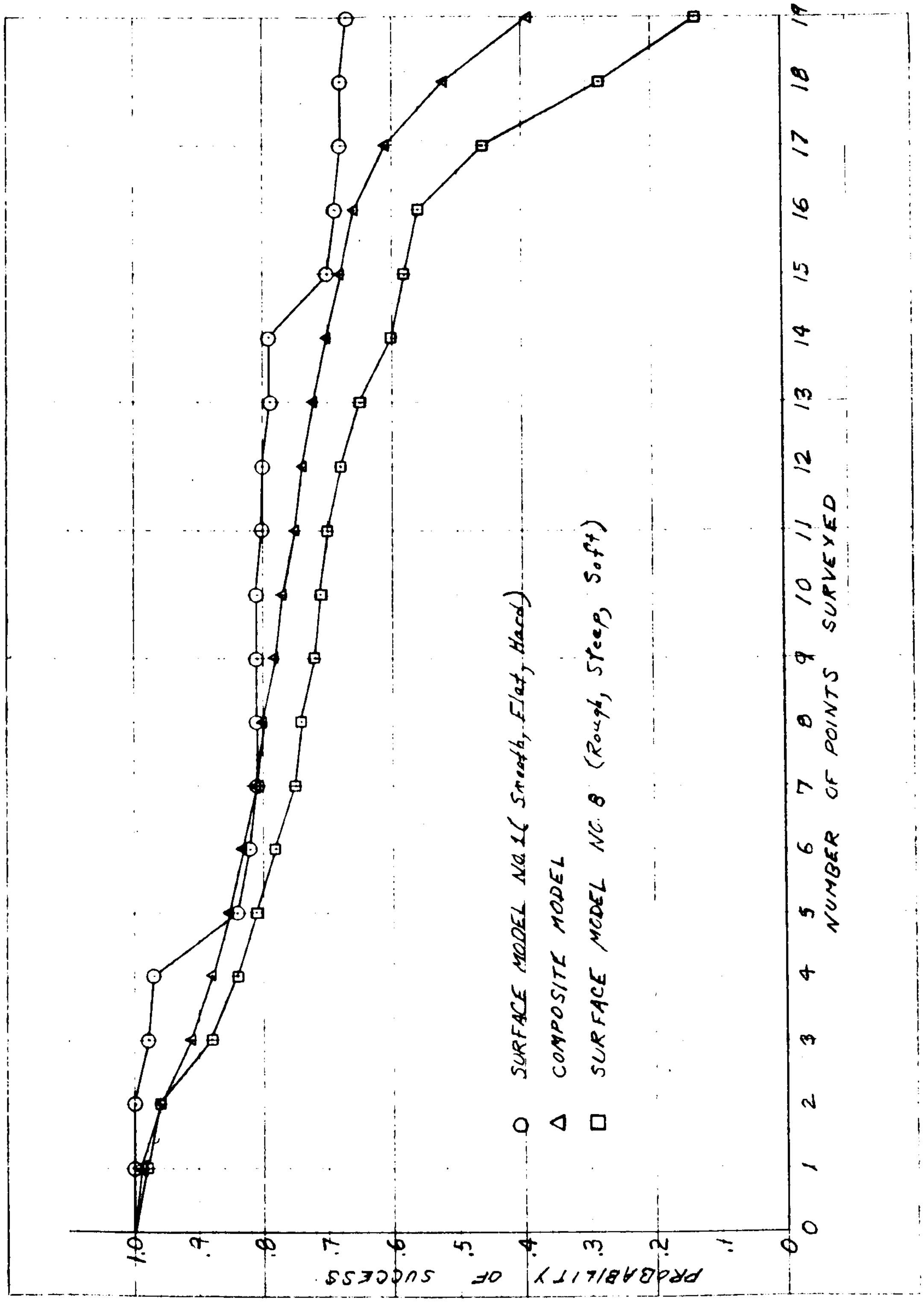

Figure 3-22 Probability of Success for Adaptive Mission

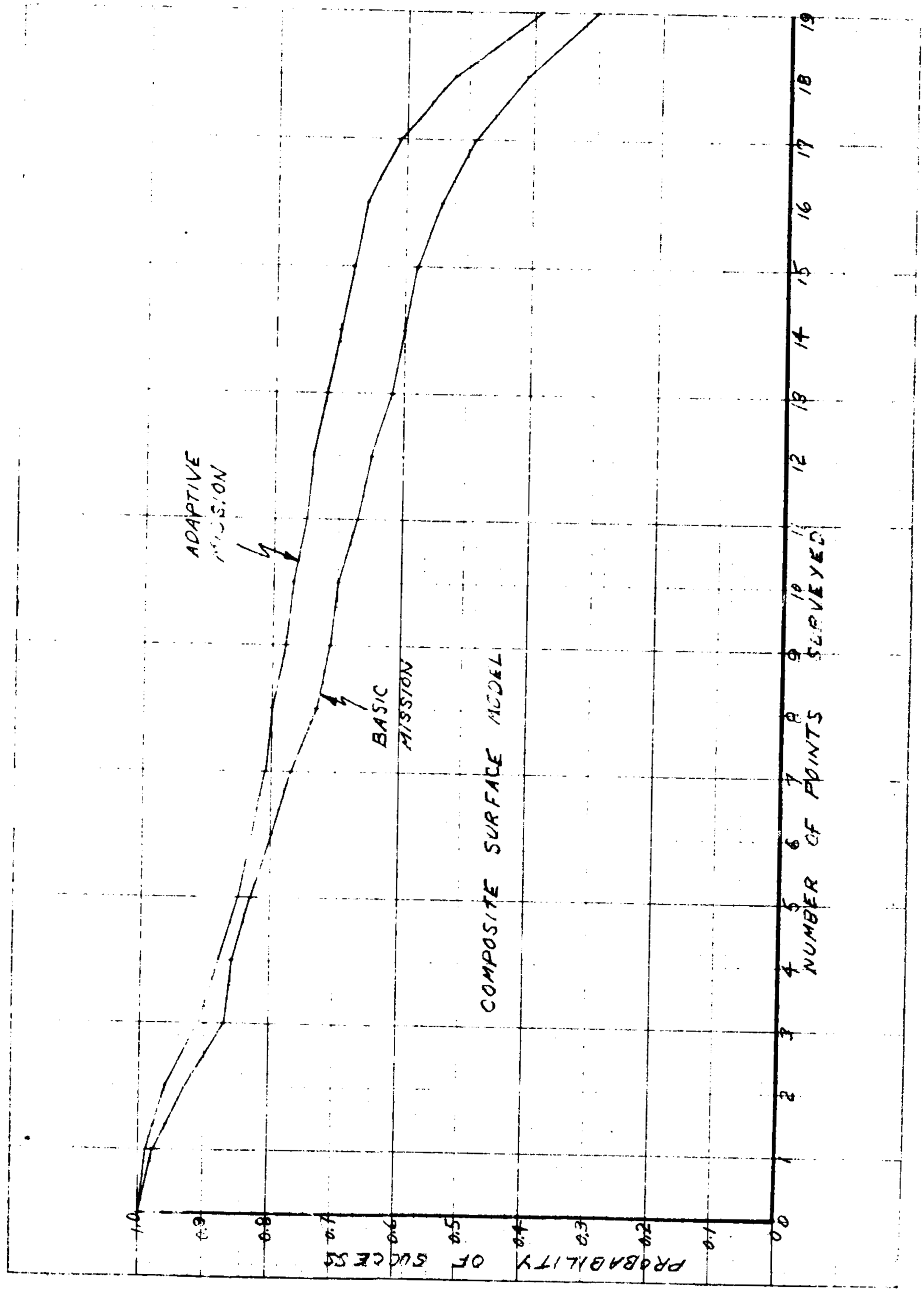

Figure 3-23 Comparison of Basic and Adaptive Mission Success

0.39 for a gain of 0.09 or approximately one-third. Verification of 13 points, defined as the minimum mission, shows a gain from 0.62 to 0.72 (14%) in the probability of success. Thus, the relative gain is greater as the mission is extended.

The gain in mission success probability achieved by the adaptive mission is of course directly related to the shorter mission times and attendant reliability gains. The magnitude of the saving in mission time is shown in Figure 3-24 for all surface models. The times for the basic mission are identical to those shown in Figure 3-16. The average mission time dropped approximately 1-1/2 months, resulting in a value of slightly over three months. This represents a reduction of about 35%.

The mission distance under the adaptive approach is roughly the same as for the basic mission which was shown in Figure 3-16 and therefore is not shown.

3.3 ROVING PATTERN STRATEGY

The strategy for choosing between various roving patterns (overall site verification patterns) cannot be detailed without first looking at the strategy which might be employed throughout the SLRV program. Thus, the approach in this section will be to first discuss overall program strategy, followed by the s trategy required for an individual mission. Finally, an example will be given of the application and results of the basic rules of strategy for the 19-point verification mission.

3.3.1 Program Strategy

A simplified representation of the problem of program strategy is shown in Figure 3-25. On the far left, a few of the elements entering program strategy are shown. Thus, given the SLRV program requirements, the problem is one of determining how best to fulfill these with a given number of flights. The main point to be made here is that strategy for individual SLRV missions should not necessarily be identical for all flights. The strategy is defined by the over-all program goals, the number of flights in the program, current knowledge of the lunar surface, and a multitude of other considerations. Data from all sources, which include terrestial observations, Ranger, and early Surveyor flights, etc., should serve as bases for the lunar surface model and, therefore, mission strategy.

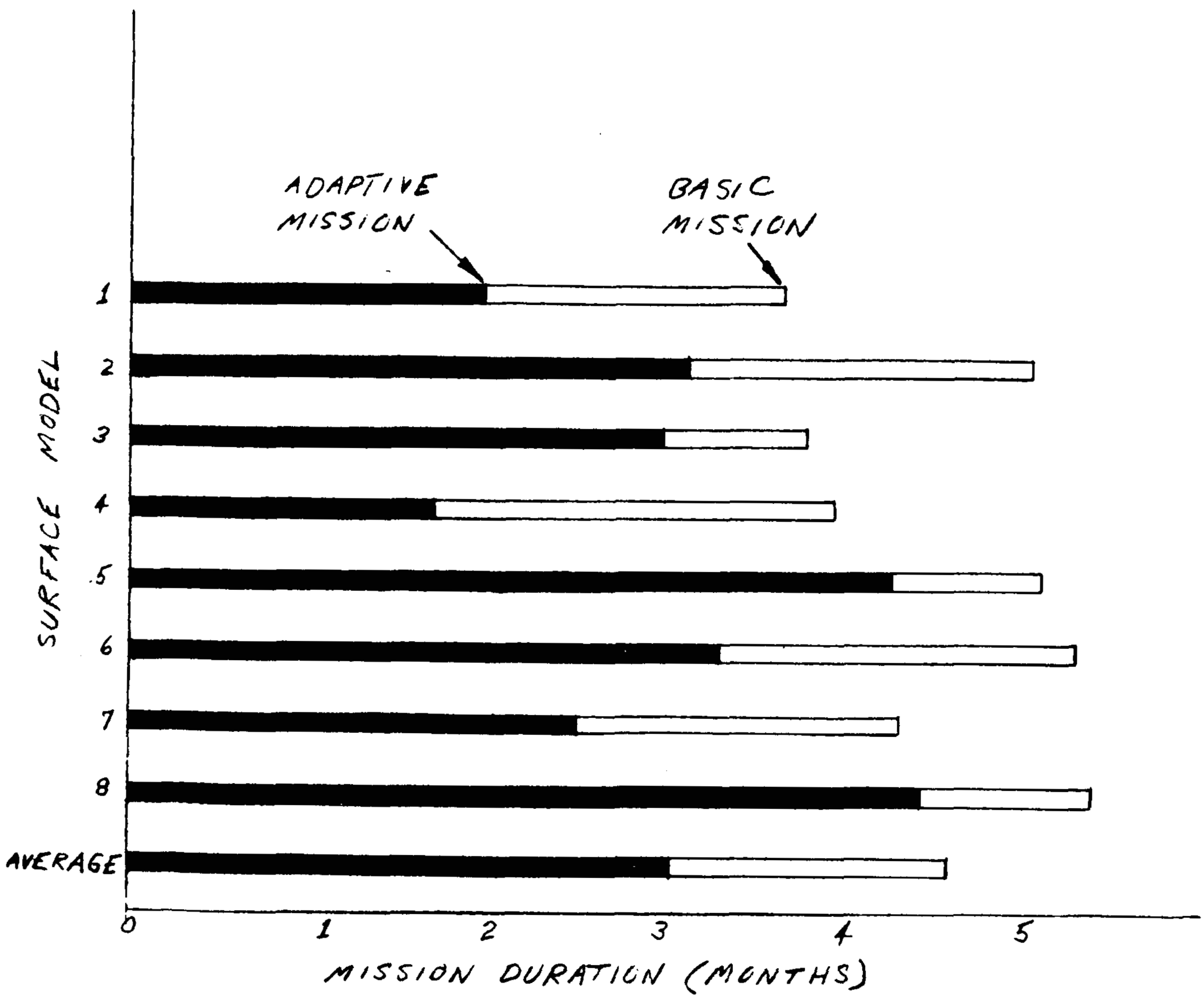

Figure 3-24 Effect of Surface Model on Mission Duration for Adaptive Mission

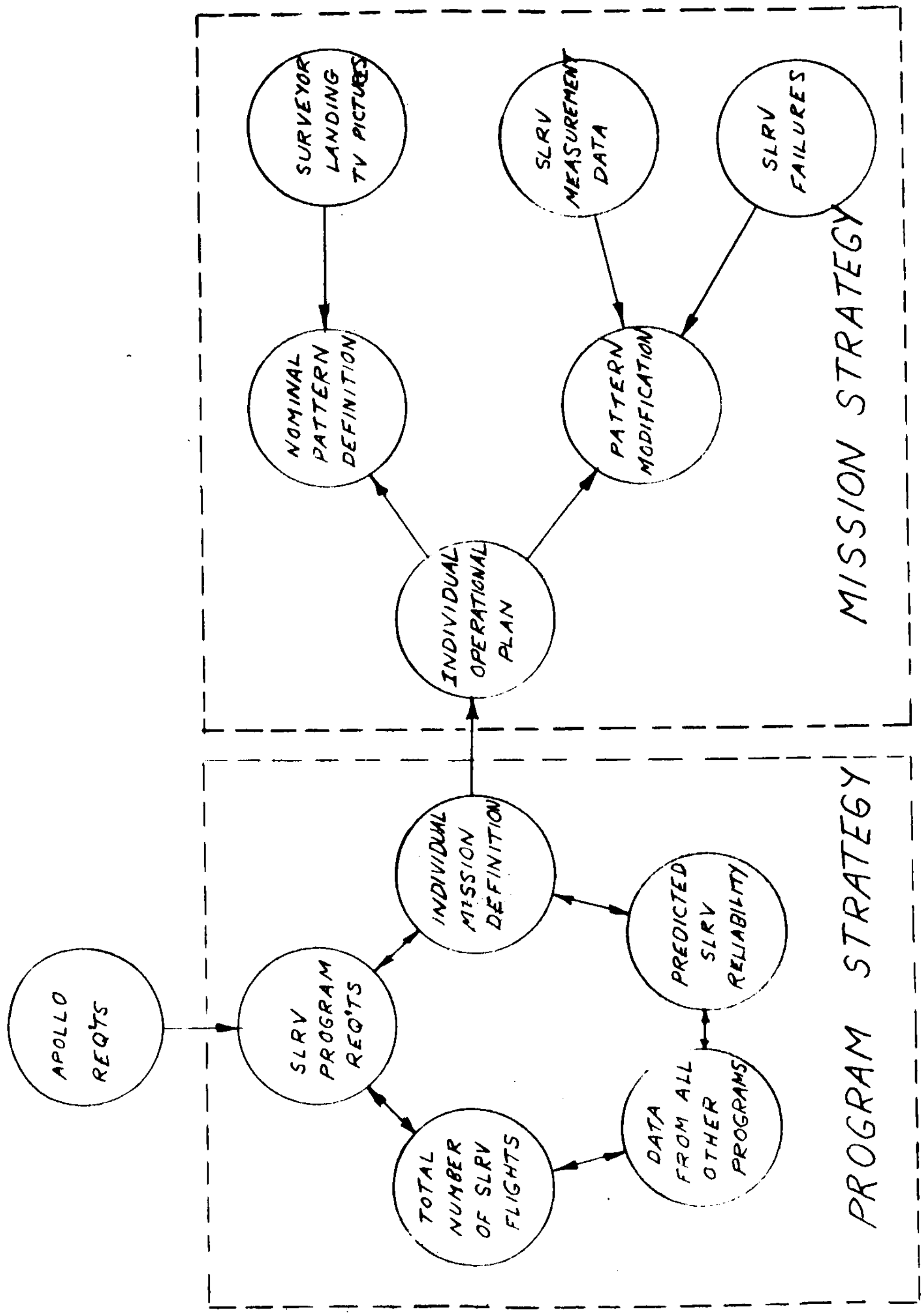

Figure 3-25 Definition of Mission Strategy

The predicted SLRV reliability will also be a factor in individual mission definition. It seems reasonable that early missions would be shorter and simpler in order to achieve a high probability of success. With reliability growth in the middle and late program stages, the missions will increase in complexity and duration in keeping with the improved reliability.

As Figure 3-25 indicates, the output of the program strategy is a definition of the mission for each flight. As data are received from other programs and from early SLRV flights, the program strategy may be modified. Likewise, as the number of SLRV flights is increased or decreased, the individual flight missions must be modified.

3.3.2 Mission Strategy

Mission strategy is defined as the plan for operating the vehicle on the lunar surface. This plan must include, not only the means of choosing the basic pattern to be covered, but also the criteria for modifying the pattern on the basis of data returned.

The basic question which determines the pattern to be followed is the knowledge of the lunar surface at flight time. Two fundamentally different approaches may be taken in any flight:

1. Area sampling
2. Point verification.

In area sampling, the SLRV travels over the surface according to a pattern designed on a statistical basis. Every measurement taken by the SLRV is treated as a sample, and the nature of the surface is predicted on the basis of the number of samples taken, the acceptability of each measurement, spacing between measurements, etc. On the basis of the early measurements, the pattern is modified to cover succeeding areas in lesser detail, relying on statistics to provide the degree of confidence in the total site acceptability.

In point verification, the total area is not covered. A number of points of sufficient size for a LEM landing are 100% verified and located throughout the landing site in a pattern permitting the LEM to reach at least one from any hover point above the landing site.

There are two fundamental differences between the two approaches:

1. The degree of lunar surface homogeneity which must be assumed in using each approach.

2. The applicability of each approach to adverse surface conditions.

In the area sampling approach, considerable homogeneity is assumed. That is, in order to obtain the required confidence in the entire area on the basis of a reasonable number of measurements, one must assume that the samples within the 3200-meter site come from a given distribution and that a small sample area will yield the same distribution. However, it is easy to see that if, for example, large soft areas abound in low sample areas, the conclusions drawn on the basis of highly-sampled good areas will be erroneous. This is illustrated pictorially in Figure 3-26 where in effect a spiral pattern is assumed, with sampling decreasing as a function of distance from the center. To avoid this difficulty, either the sampling rate must be retained at a fairly high level, meaning many measurements with long mission times, or an assumption of homogeneity in areas much smaller than the site size must be made.

With the point verification approach, no assumption of homogeneity need be made, since the points are 100% verified and the intervening areas are of small importance to LEM. The need for a large number of measurements is also avoided because of the extremely small percentage of total area verified.

The applicability of each approach to adverse terrain is also very important. With a given vehicle, regardless of its mobility capabilities, the approach should allow the vehicle to accomplish the mission objective under the most adverse surface conditions. If the marial areas prove to be quite favorable, being perhaps 90% acceptable to LEM, the verification approach is of lesser importance. That is, either the area sampling or the point verification approach will provide the required verification confidence. Even with this favorable surface, the point verification approach can increase the LEM probability from 90% to nearly 100% which makes this approach superior even for a good moon.

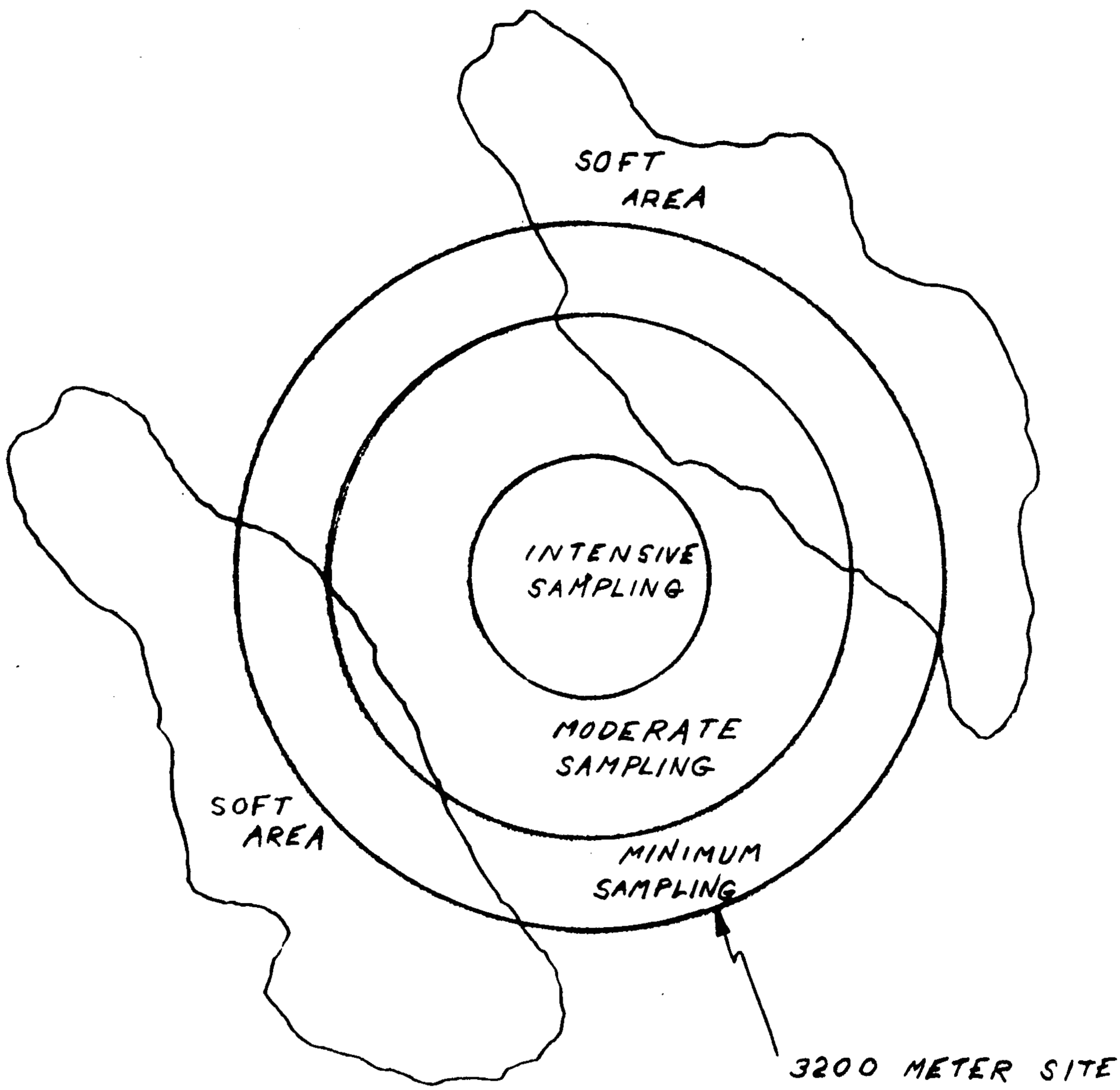

Figure3-26 Area Sampling in Terrain Containing Large Unacceptable Areas

If the lunar surface proves to be quite adverse, say 40% unacceptable to LEM, the gap between the two approached widens greatly. Even if a vehicle is able to sample 100% of such a lunar surface on an area (statistical) basis, the site must be rejected because only 60% is acceptable and EPD-98 is not satisfied. On the other hand, the point verification approach still results in a successful mission, with the acceptability of the verified site approaching 100% in an area which overall is only 60% acceptable. This is illustrated in the example discussed in Section 3.3.3.

From the above discussion, it appears that early SLRV flights might well be operated in the area sampling mode to cover a large area and thereby refine our knowledge of the surface. For subsequent flights, the point verification approach appears to be superior in accomplishing LEM site verification, since it provides the maximum probability increment for a given surface. Thus, the bulk of the strategy studies have been concentrated on the point verification approach.

The Point Verification strategy will now be defined as consisting of two parts:

1. Point location determination (pattern layout)

2. Point survey orientation.

3.3.2.1 Point Location Determination

Assume that the basic pattern to be followed is as shown in Figure 3-1. This pattern will be followed in a clockwise manner as shown. The pattern must be tentatively located and oriented following touchdown as indicated in the upper right of Figure 3-25 on the basis of Surveyor pictures taken during the landing phase. In principle, an overlay of the pattern is placed upon the Surveyor picture to determine, based on the amount of detail available, the best choice for:

1. Pattern location

2. Pattern orientation.

Thus, the pattern is moved over the picture and a nominal choice made on the basis of such factors as the number of potential points lying in areas which appear acceptable. This is the first point of strategy: setting the goal for the mission.

Once the mission has begun, SLRV data become available as indicated in Figure 3-25. The next major point of strategy is the procedure to follow upon encountering impassable areas. Until some data are available which describe the likelihood of saving distance by going in a certain direction when encountering certain surface features, a simple rule may be used: turn so as to minimize the departure from the straight ahead direction. The purpose of this point of strategy is to follow geological formations in the general direction of travel and avoid making turns exceeding 90°.

If, after arriving at a tentative point location, it is found that the location is impassable or unacceptable, the rule of strategy is to attempt to relocate the point on a line at right angles to the straight-line leg, on the side closest to Surveyor. Both this rule and that discussed in the previous paragraph are illustrated in Figure 3-27. The latter rule results in shrinking the pattern size while rotating the point locations about the pattern center (assumed as Surveyor). Since the pattern is originally designed to provide minimum overlap while maintaining complete coverage by the circles of LEM translational capabilities, this shrinkage merely increases the amount of overlap while decreasing the probability of success by reason of the lower overall verification radius. If alternate point locations were tried on the opposite side from Surveyor, at Point A of Figure 3-27 it is quite likely that holes from which LEM could not reach a verified point would be left in the coverage. The question naturally arises as to how far to distort the pattern by moving a single point inward. Results to date show that moving the point by 50% of the interpoint spacing (528 m) is about the practical limit. If a point cannot be found within this distance, the point is abandoned, and the next point survey is attempted. Assume that point No. 6 of Figure 3-1 is abandoned. When the SLRV is completing the next ring of points (14, 15, and 16 of Figure 3-1), points 15 & 16 would then be moved inward to partially fill the hole. It should be noted in passing that since surface maps have not yet been incorporated in the simulation, the decision as to whether to abandon a point is arbitrarily set at a number (presently 4) of unsuccessful tries. However, as indicated above, the strategy of whether to abandon a point is actually a question of how much pattern distortion will be permitted.

——— Nominal Path and Point Locations

------ Actual Path and
Point Locations

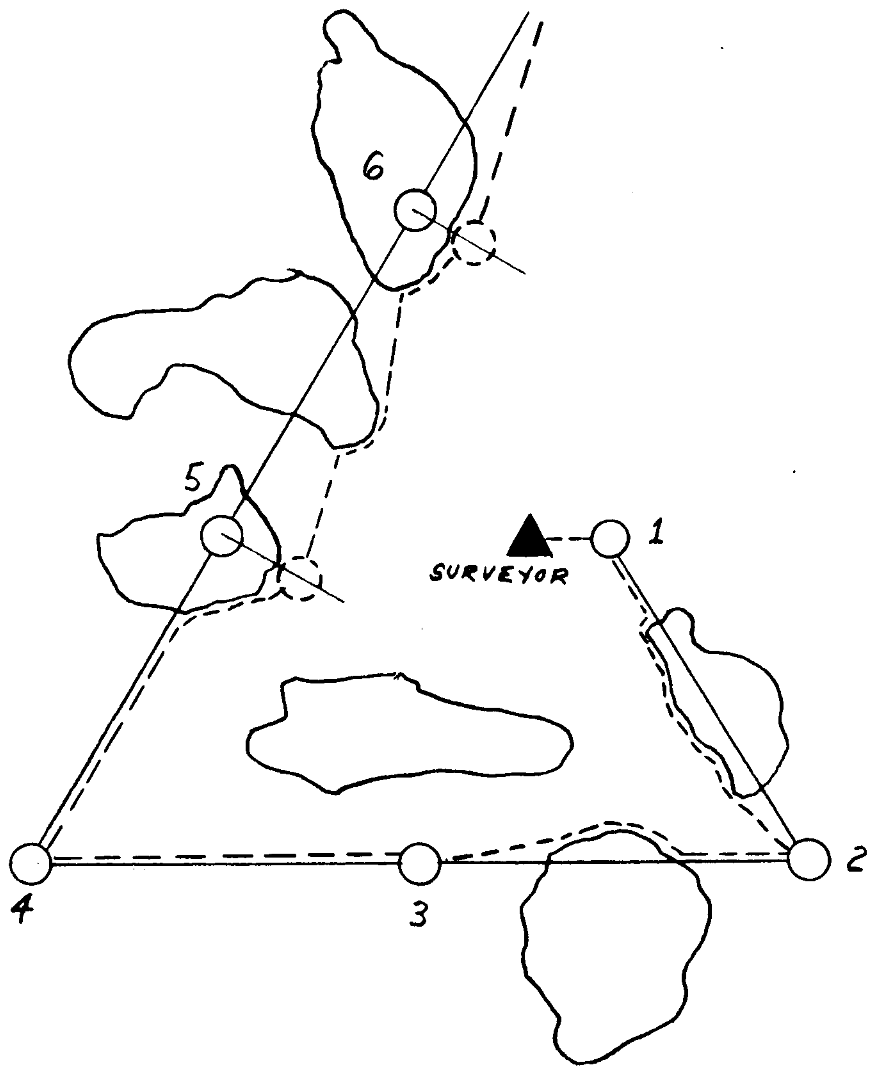

Figure 3-27 Rules of Strategy

The question of holes or voids in the pattern was mentioned briefly above. Holes will occur in actual missions primarily because of bad terrain and secondarily because of misjudgement as to the acceptability of a particular point. That is, because of the amount of data to be processed to make the acceptability decision, decision errors may quite possibly occur. A point may initially be scored as acceptable, only to prove later to be actually unacceptable. If the SLRV has completed the 19-point mission, it may return to find a good point where the error was made. If, however, the mission has been terminated and the hole is then found to exist, the strategy is to move the LEM aim point from the center of the pattern in a direction radially opposite to the hole. This is illustrated in Figure 3-28. The amount of the aim point relocation is a function of the distance of the hole from the center of the pattern. Since a hole in the center, where the highest percentage of LEM flights would land, is more serious than a hole on the pattern periphery, the relocation of the aim point is a maximum when the hole is in the center and drops off for holes at the periphery. The amount of this relocation has not yet been computed.

It may become apparent after several points have been examined that the area chosen initially is not suitable for the pattern. Thus, as in the upper portion of Figure 3-29, points 1 and 2 may have been verified, and efforts to locate points anywhere in the large bad area have failed. The pattern will then be moved to the alternate position shown in the lower position. The points already verified now form the outer perimeter of the pattern rather than the center. The net result is that most of the points already verified may be used in a second pattern and the SLRV proceeds to verify the remaining points. Studies to date have shown that, if bad spots are comparable in size to the pattern size to the pattern size as in Figure 3-29, the pattern must be moved. If bad spots are smaller, say of a size comparable to the point size, the pattern is not moved but is only distorted by moving the points. As bad spots get very small and very dense, the whole area becomes unacceptable, and the LEM landing success probability is too low to attempt landing.

The final item in the point location strategy is how to proceed when vehicle failures are imminent or have already occurred, degrading performance but not causing mission abort. The stand taken here is that the possibility of failures is properly the domain of program strategy as discussed in Section 3.3.1. Each mission must be planned with the reliability prediction in mind. When partial failures actually occur during

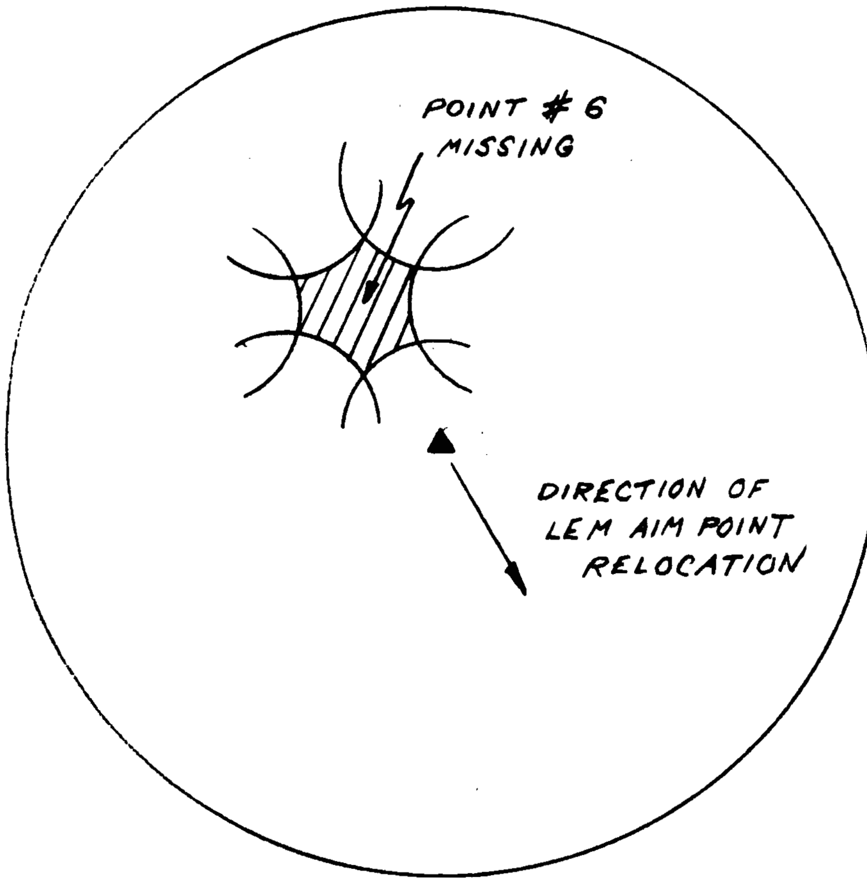

Figure 3-28 LEM Aim Point Adjustment

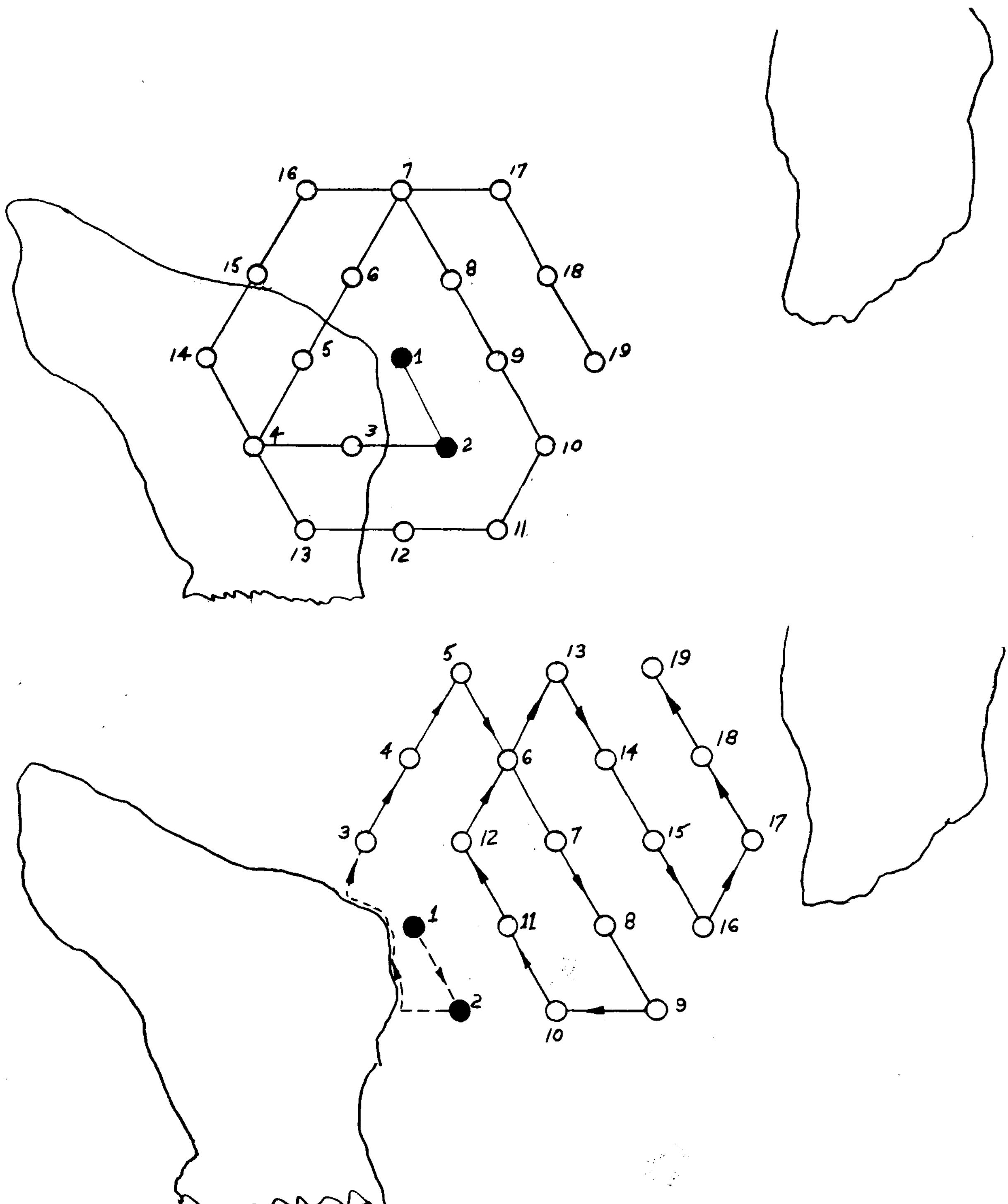

Figure 3-29 Pattern Relocation

a mission, the mission should not be changed in concept but merely proceed as planned, albeit at a slower pace. It might seem that, knowing a particular failure has occurred, the remaining lifetime should be predicted and the measurement plan changed, e.g, to cover the maximum possible area in the remaining time. However, within the program planning, a specific mission definition might call for 13 points to be verified. If 13 points has been unequivocally defined as the minimum required before LEM will land, there is little to be gained in changing the mission to achieve a hasty look during the final mission hours. A possible exception is that, if the failure renders 13-point verification impossible, the remaining lifetime may be spent in examining wider areas of the lunar surface to add to general scientific knowledge. However, this is the domain of program strategy and is not to be decided upon except in detail after a failure has actually occurred on a given mission.

3.3.2.2 Point Survey Orientation

One detail of over-all strategy which has not received too much attention, and justifiable so, is the orientation of the individual point survey patterns. In particular, it is recognized that the point survey pattern can be oriented north-south, east-west, etc. Each survey within a point will probably be oriented differently. Assuming that crevice detection capability as a function of incident illumination is known, the point survey pattern may be oriented to maximize safety as the sun angle changes. Another factor in point survey orientation is the effect on navigation errors because of the orientation of the survey relative to Surveyor (for RF ranging). At the present time, the optimum orientation of the point survey has not been defined as a function of all factors in combination. This is a portion of strategy, however, and must be defined as the factors and their effects are further defined.

3.3.3 Example of Mission Strategy

As an example of the application of the few simple rules of strategy of Section 3.3.2, the details of a 19-point mission on an adverse moon will be discussed. It will be shown that the point verification approach permits a LEM landing on this adverse surface, whereas the sampling approach does not. The surface is purposely assumed to be 40% "bad", where "bad" is for simplicity defined as both impassable for the SLRV and unacceptable to LEM. By choosing such a surface, the possibility of verifying the area by the area sampling approach is outlawed by definition, since the requirement (EPD-98) states that 70% of the area must meet requirements with 99% confidence. Even with a vehicle capable of traversing this assumed surface entirely and of sampling it 100% ("bad" now defined as unacceptable to LEM), the area must still be rejected for LEM landing, since only 60% of it is good by definition. Yet, by using the point verification approach, the LEM may land on this surface with a probability of success of approximately 0.988 with 100% confidence.

A map of the surface containing 40% bad area was constructed using the technique discussed in Section 3.1.2.2, under the heading "Time, Distance Relationships - Interpoint Travel". The mission was then defined as verification of 19 points in the pattern of Figure 3-1(a). It was assumed that the Surveyor landing was in a good area so as not to penalize the SLRV for bad landings. Also, since 40% of the area is bad, the pattern was initially positioned to give eight points (42%) in bad or marginal areas. Placing the points in bad areas is the same as assuming that the pictures taken during the Surveyor landing were either not received or did not permit recognizing the bad areas. Starting from point (1) then, the pattern was followed in a clockwise manner under the rules of Section 3.3.2. In particular:

1. When avoiding hazards, turn so as to move as close to straight ahead as possible.

2. Move at right angles to the last interpoint line and towards Surveyor when searching for a good point location.

3. Restrict the distance travelled in (2) to 50% of the interpoint spacing and move to the next point in the pattern.

4. Fill in any holes caused by restriction (3) by an inward shift of the points of the next outer ring.

Figure 3-30 shows the results of applying this strategy to the 40% bad surface. The nominal pattern is shown in solid lines; the dotted lines indicate the SLRV path. Circles defining the limits of LEM translational capability have also been shown to indicate the coverage of the area in the presence of the pattern distortion. Note that points 14 and 16 were abandoned, because the SLRV could not find a reasonable path to them. Also,

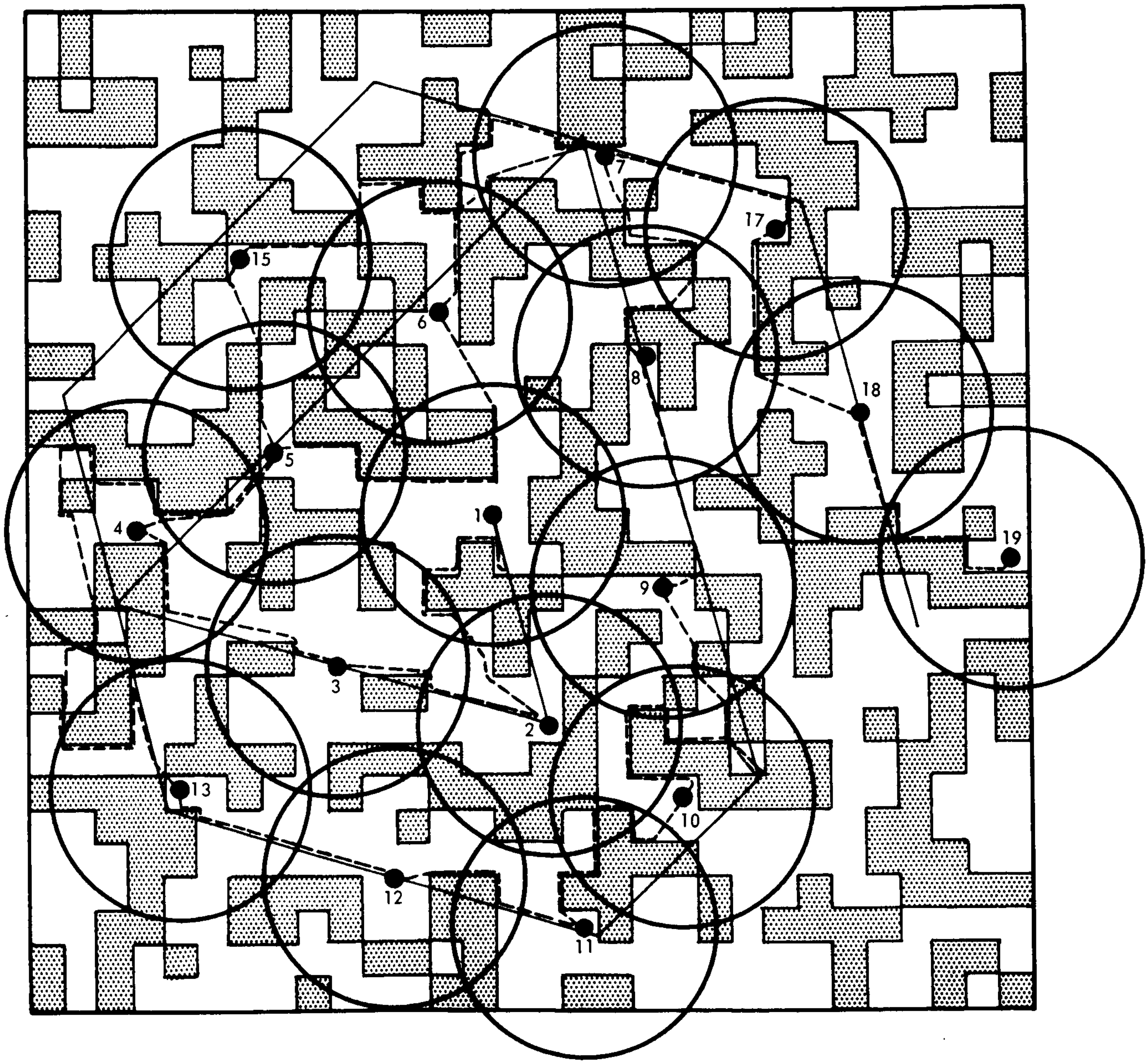

Figure 3-30 Example of Strategy Application

point 19 was placed outward from Surveyor leaving a hole in the pattern. By referring to Figure 3-2, the probability of LEM landing on this surface is 0.988, since the effective verified diameter is about 1880 meters.

Thus, it is seen that (even with a few simple rules) 17 points were surveyed giving a probability increment of 0.388 over the best possible result using area sampling.

SECTION 4

EVALUATION OF HEAVIER VEHICLES

Section 3 presented an evaluation of the 100-lb SLRV design. This section presents evaluations of vehicles up to 150 lb in weight. Five designs are first summarized, each representing a reasonable design for the stated weight. These designs are described in detail in Volume II, Section 6.

These evaluations are based on simulation results using the procedures followed in the evaluation of the 100-lb SLRV. The primary evaluation objective was to determine the probability of success for the 19-point mission. Lesser objectives were to determine success probabilities for partial mission objectives and to define the achievable saving in mission duration with the heavier vehicles.

Evaluations for the basic mission are given first, followed by those for the adaptive mission.

4.1 SYSTEM DESCRIPTIONS

Table 4-1 presents in summary form the vehicles which were evaluated. For greater detail see Section 6, Vol. II.

TABLE 4-1

SUMMARY OF HEAVIER VEHICLES

System Weight (lb)	Obstacle Climbing Capability (cm)	Weight Allocated to Redundancy (lb)	Operating Speed (mph)
110	40	0	0.07
120	50	5	0.07
130	60	2	0.18
140	70	10	0.18
150	100	10	0.18

4.2 PROBABILITY OF MISSION SUCCESS

4.2.1 Basic Mission

The probability of mission success for the basic mission with heavier vehicles is given in Figure 4-1. The 100-lb curve is also shown for comparison. Only the 110- and 150-lb systems are shown, since these are sufficient to show the extent of the increase. With the addition of 10 lb to the 100-lb system, a great increase in P_S is achievable. The increase in adding another 40 lb (150 total) is less impressive. The 110-lb system shows this disproportionately large improvement because the 110-lb operation is based on a 24-hour DSIF availability (3 stations) whereas the 100-lb operation was limited to an 11-hour day consistent with the single 210-ft DSIF dish.

The probability of success achieved as a function of system weight is shown for both the minimum (13 point) and desirable (19 point) mission in Figure 4-2. For both missions it is seen that the great gains are to be made by adding 20 to 30 lb to the 100-lb system. For higher weights, the gains are not as significant. It would seem that with a system weight of 120 to 130 lb, the most significant gains to be made thereafter would be as the result of strategy; in particular, optimizing the pattern to be followed.

An interesting study was made to evaluate the mobility benefits of allocating weight allowances above 100 lb. With all parameters of the 100-lb vehicle remaining fixed, the simulation was run for increasing mobility capability. The results are shown in Figure 4-3. On the No. 1 surface model, no increase in success probability was achieved, which is as expected: the probability of success for this model is not limited by mobility capability of 30 cm, but mainly by system reliability.

Conversely, No. 8 surface model shows some improvement above 30 cm. However, this improvement is not large compared to the value obtained by the 30-cm design.

It may be argued that the results of Figure 4-3 are strictly dependent upon the surface models assumed. As the surface models are made more rugged, the curves will get correspondingly steeper, reflecting greater advantage in higher mobility. The problem in system optimization, however, is to select a mobility capability representing a reasonable trade-off between the surface expected and the weight allocation. For the surface models assumed, this has been accomplished in the 100-lb design at 30 cm. At higher weights, choice of the optimum mobility capability must await further definition of surface models as well as system requirements.

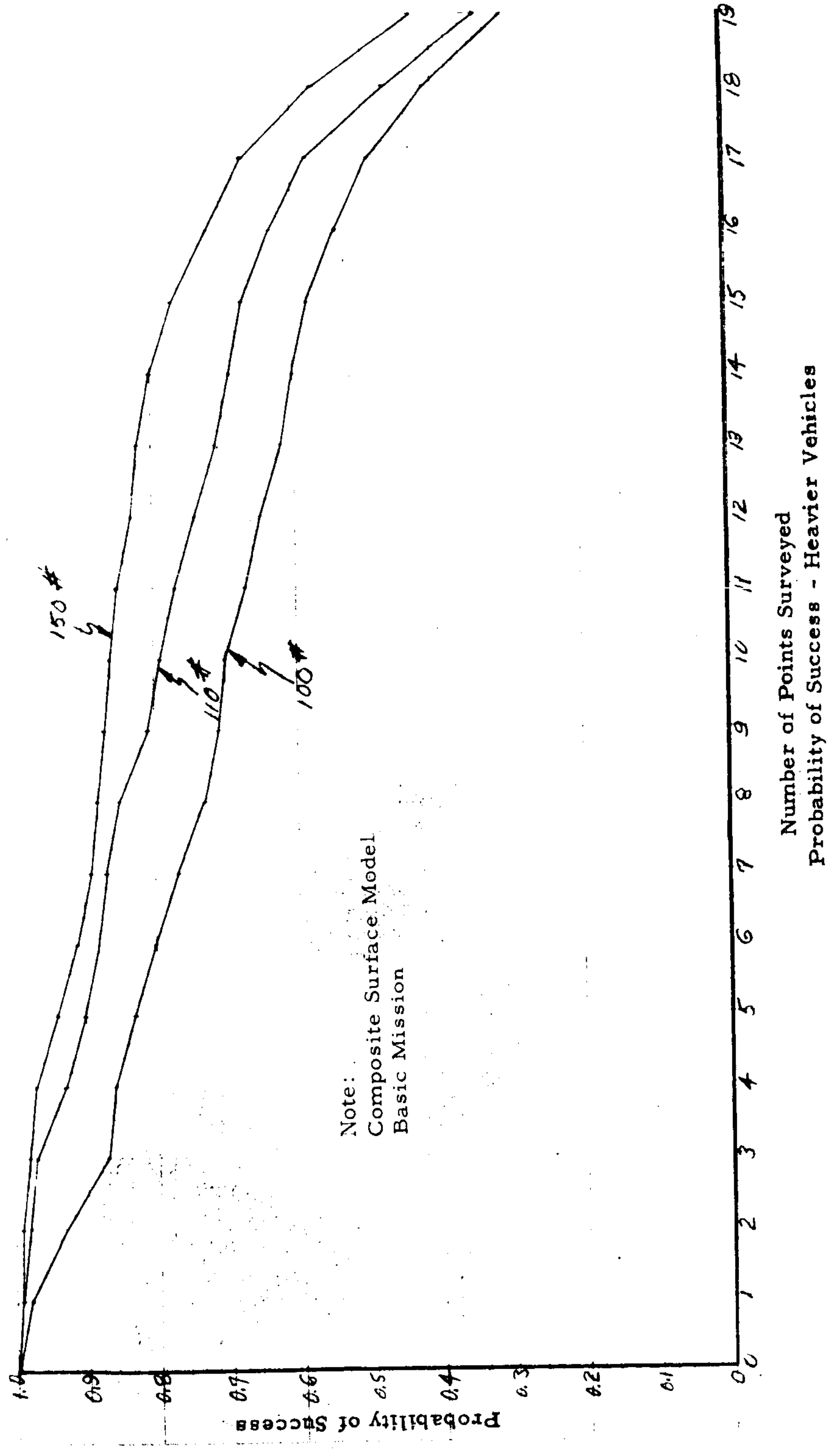

Figure 4-1 Probability of Success - Heavier Vehicles

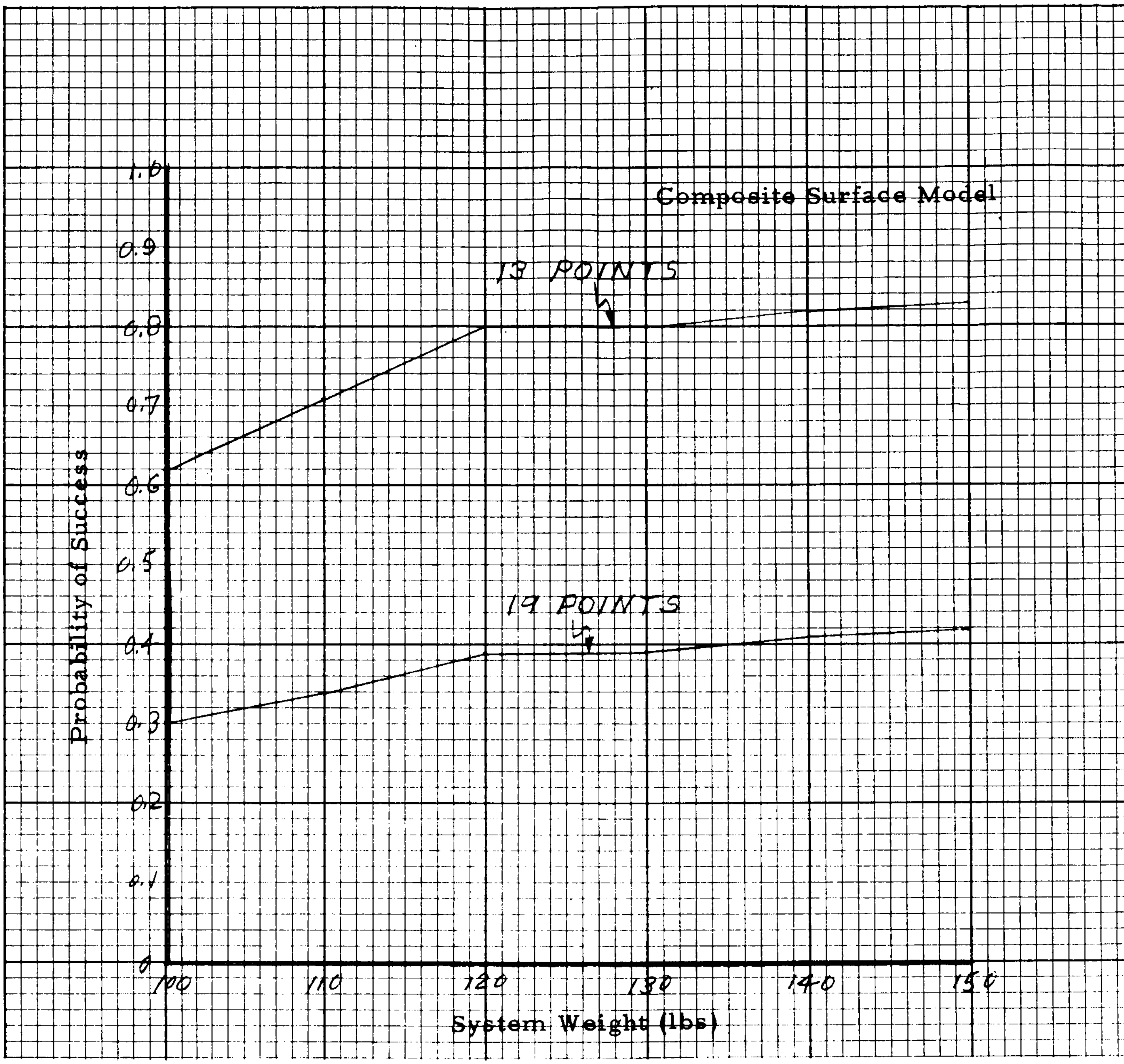

Figure 4-2 Probability of Success for Heavier Vehicles Basic Mission

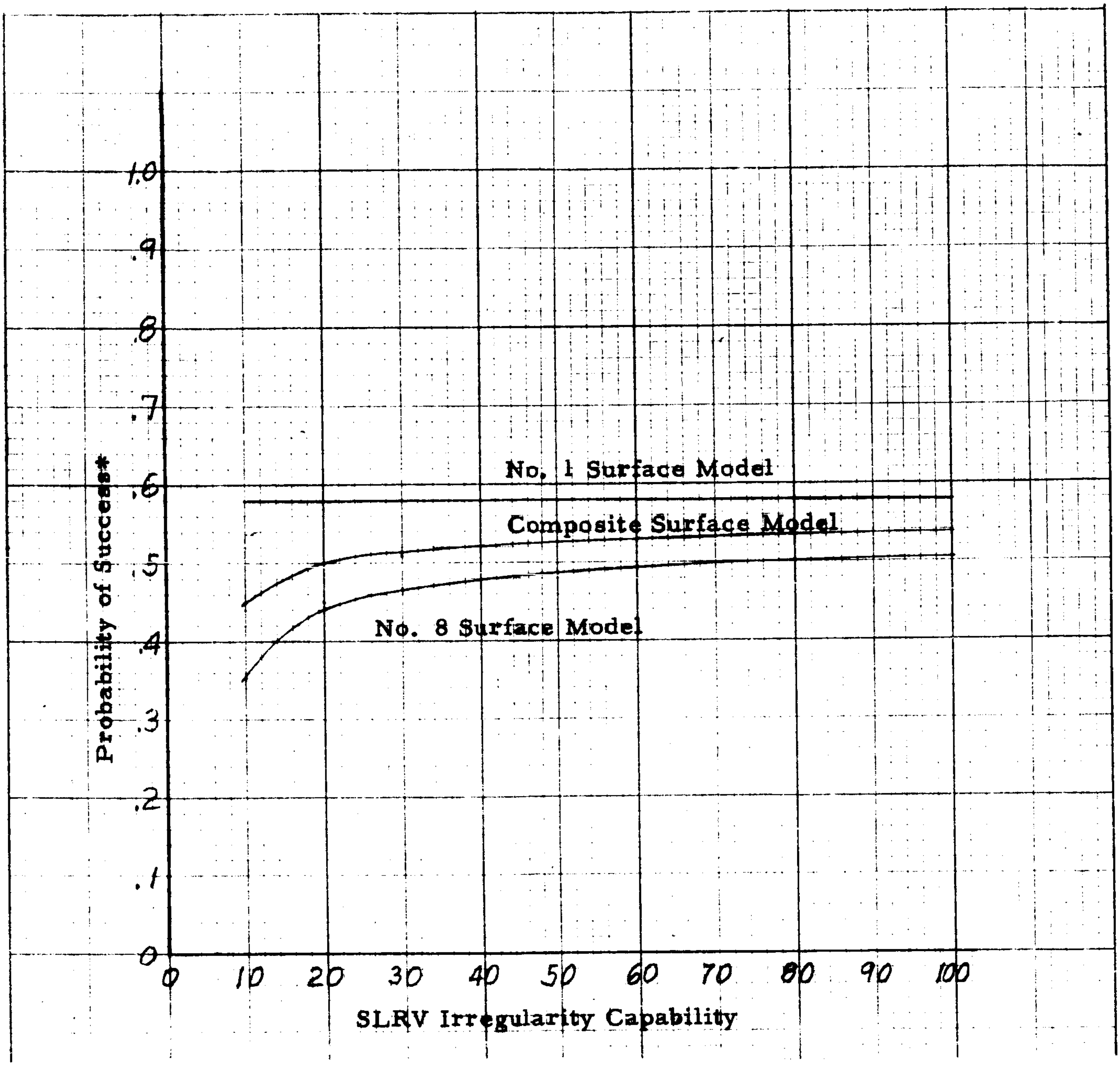

Figure 4-3 Effect of SLRV Irregularity Capability

4.2.2 Adaptive Mission

The adaptive mission was conceived to improve over the basic mission by taking advantage of favorable terrain in the more rapid completion of mission tasks. The increase in success probability for the 100-lb vehicle was shown in Section 3. The gains achievable with heavier vehicles are given in Figure 4-4. This may be compared with the basic mission by referring to Figure 4-1. For the 19-point mission the adaptive approach shows the following probability increments:

Weight	Increase in P_s	% Increase
100	0.09	30
110	0.10	29
150	0.06	14

The probability of success as a function of system weight is given in Figure 4-5. As was shown for the basic mission, system weights beyond about 130 lb show little relative gain.

4.3 MISSION DURATION

4.3.1 Basic Mission

The mission duration for the basic missions (both 19 and 13 point) is shown in Figure 4-6. The large decrease in mission time from the 100-lb system to 110 lb is caused by the switchover from the 11-hour to 24-hour operation as mentioned in Section 4.2.1 The obstacle capability and the redundancy are steadily increased in going from 110 to 120 lb and up to 150 lb. Thus mission duration falls consistently as shown. System weight of 120 to 130 lb results in reasonable mission durations of less than three months. Increasing the weight still further decreases the mission time less rapidly. Therefore, a weight in the neighborhood of 120 to 130 lb may be ample.

4.3.2 Adaptive Mission

Mission duration for the adaptive mission with heavier SLRV's is shown in Figure 4-7. Comparing these results with the basic mission of Figure 4-6 shows a rather consistent saving of one month for all system weights for the 19-point mission. The saving for the minimum mission of 13 points is proportionately lower.

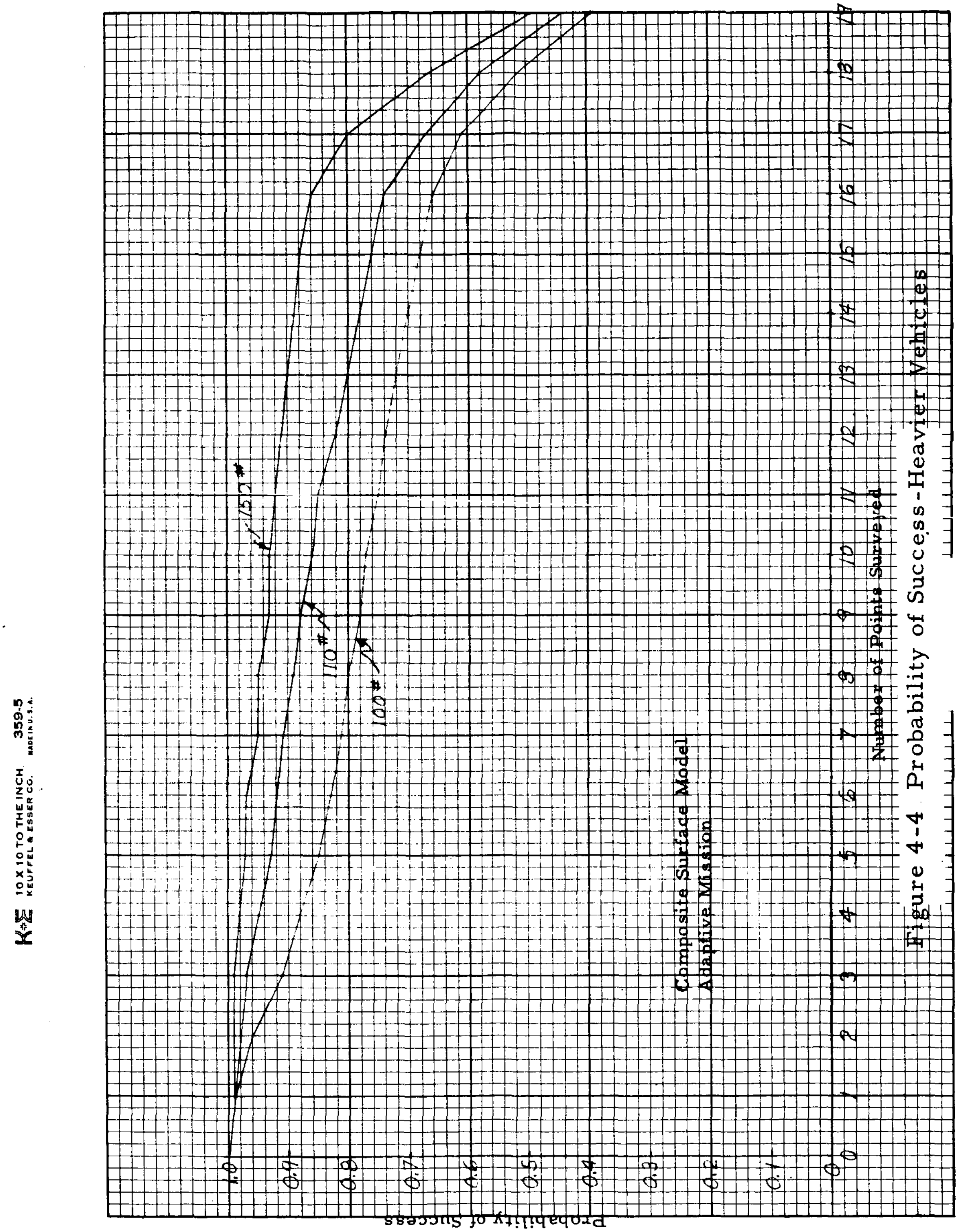

Figure 4-4 Probability of Success-Heavier Vehicles

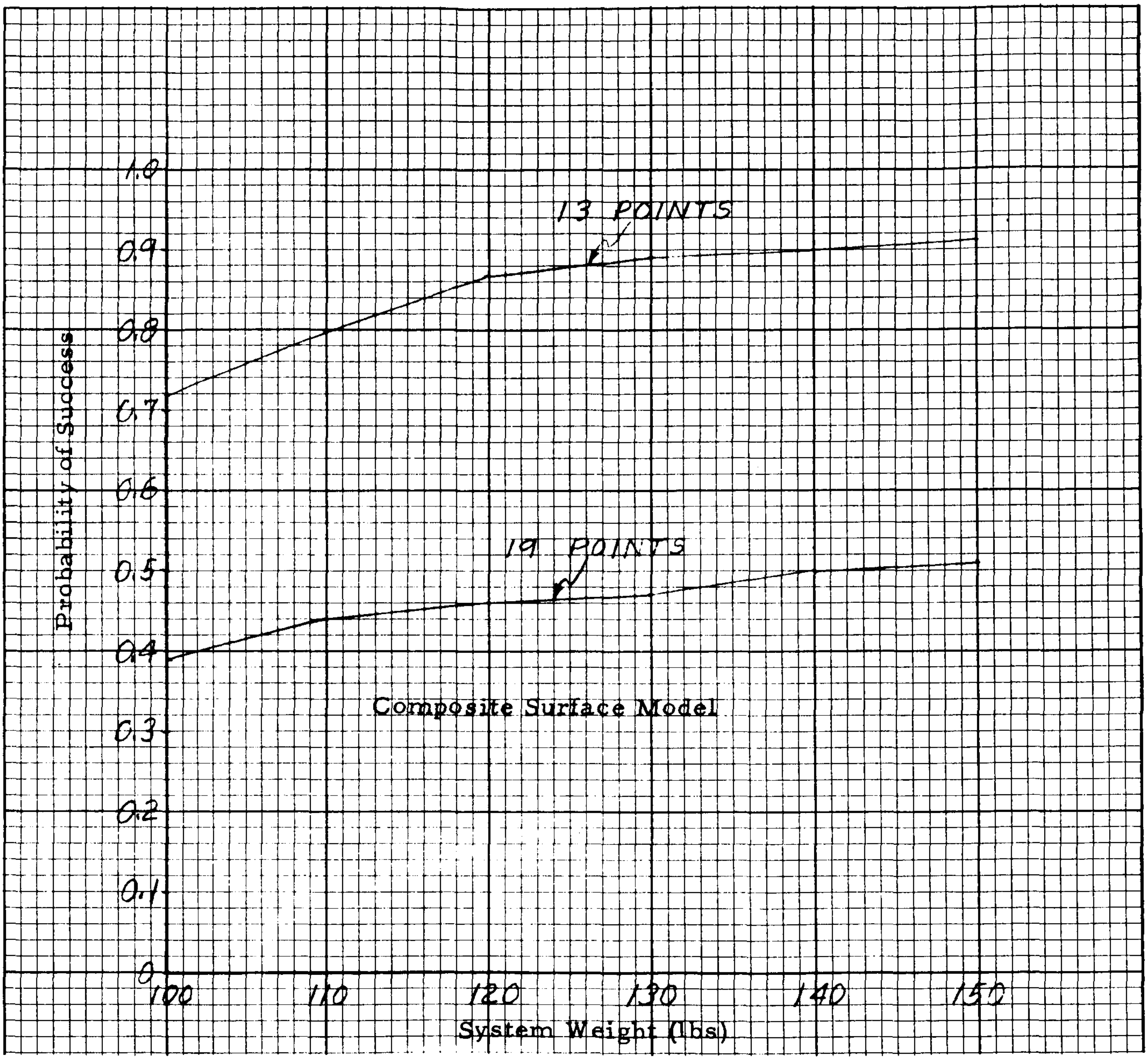

Figure 4-5 Probability of Success for Heavier Vehicles—Adaptive Mission

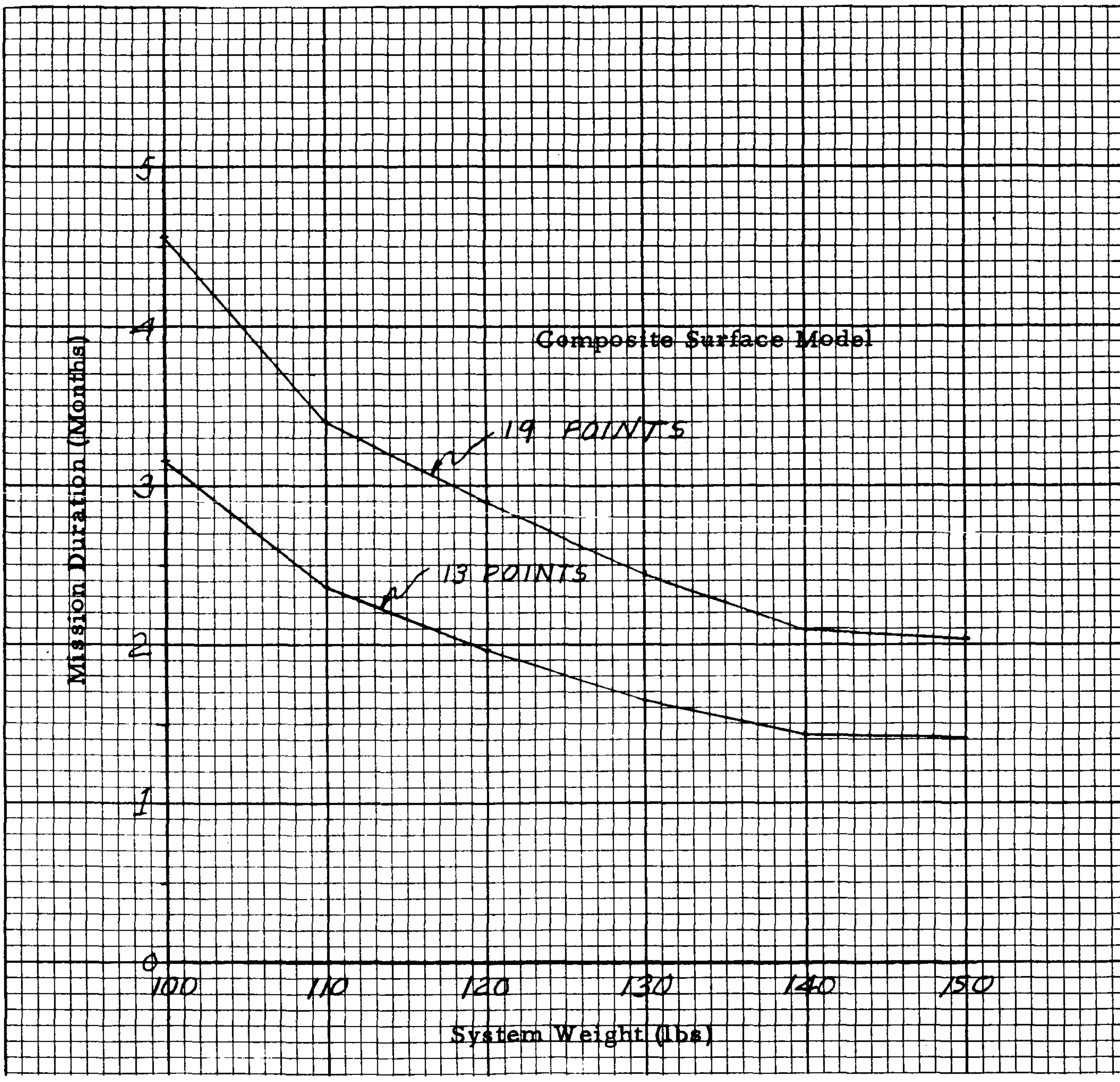

Figure 4-6 Mission Duration for Heavier Vehicles—Basic Mission

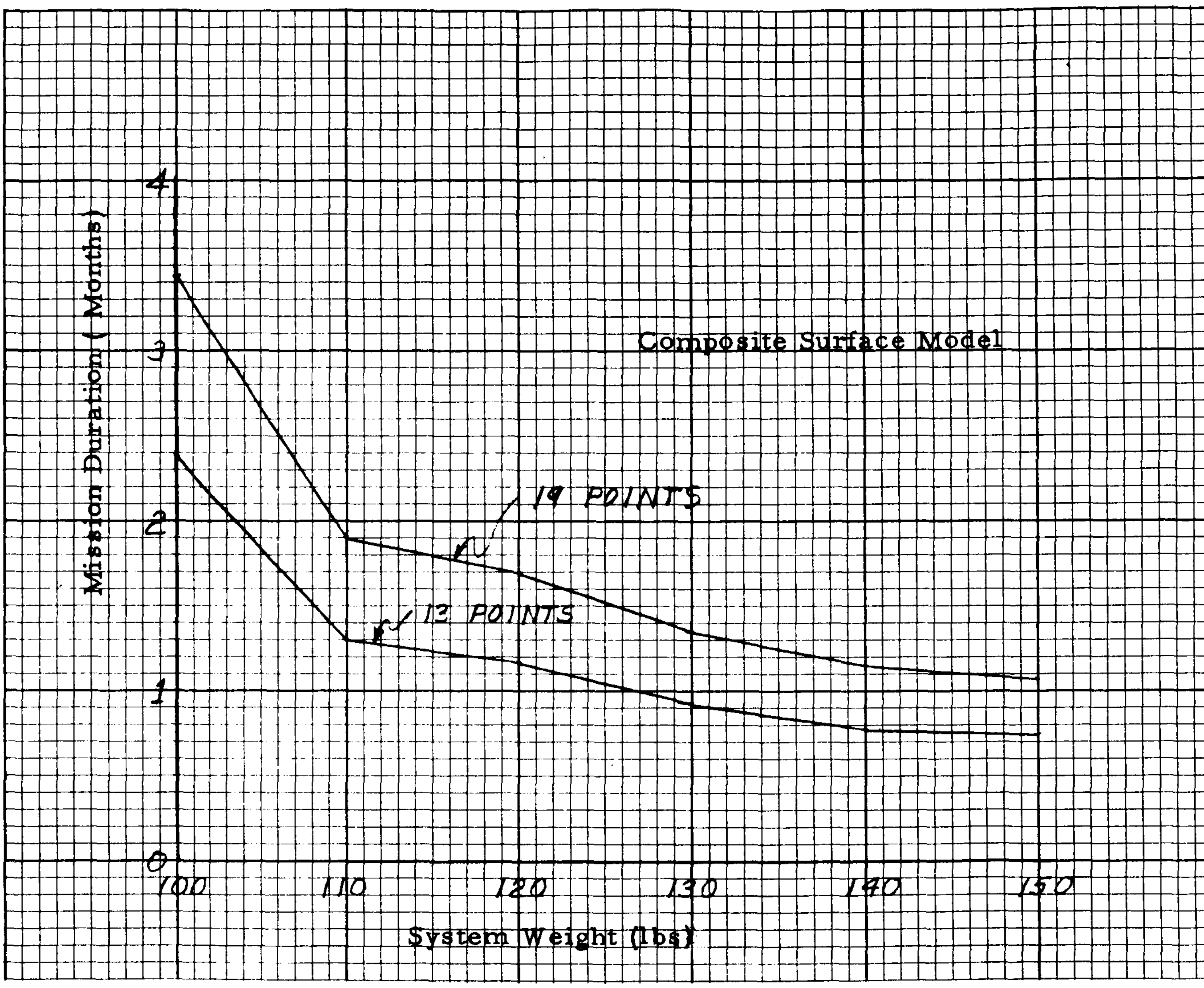

Figure 4-7 Mission Duration for Heavier Vehicles—Adaptive Mission

The variations in mission duration as a function of the eight surface models are shown for the heavier vehicles in Figures 4-8 through 4-12. The steady decrease in mission time with added weight can be seen for any model from these figures. Note that No. 4 surface model shows the best possible mission time. This model is flat, smooth, and soft and gives the most optimistic time. Adverse slopes or obstacles are not encountered, and it is assumed that no crevices exist in the soft soil. The model therefore may be likened to a flat desert area.

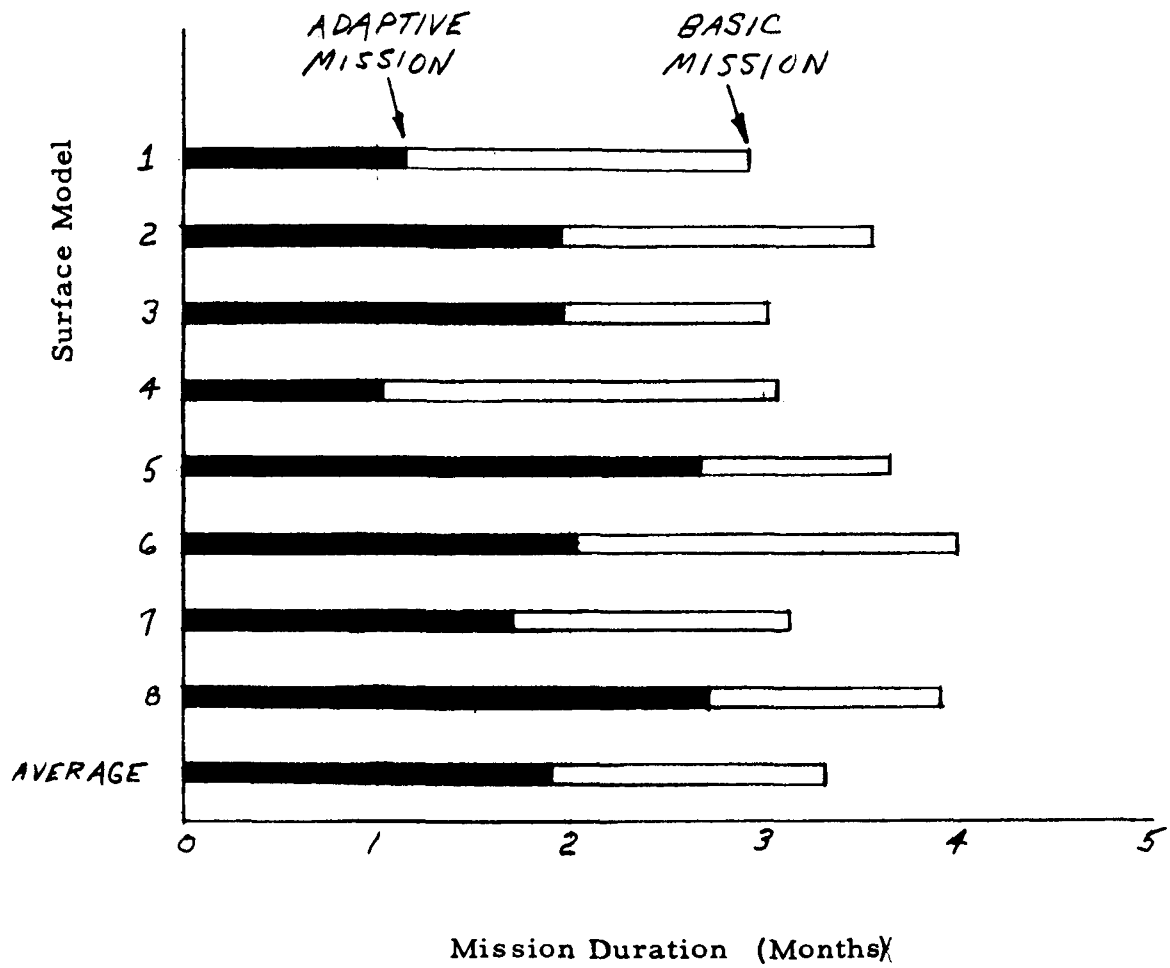

Figure 4-8 Mission Duration—110 lb System

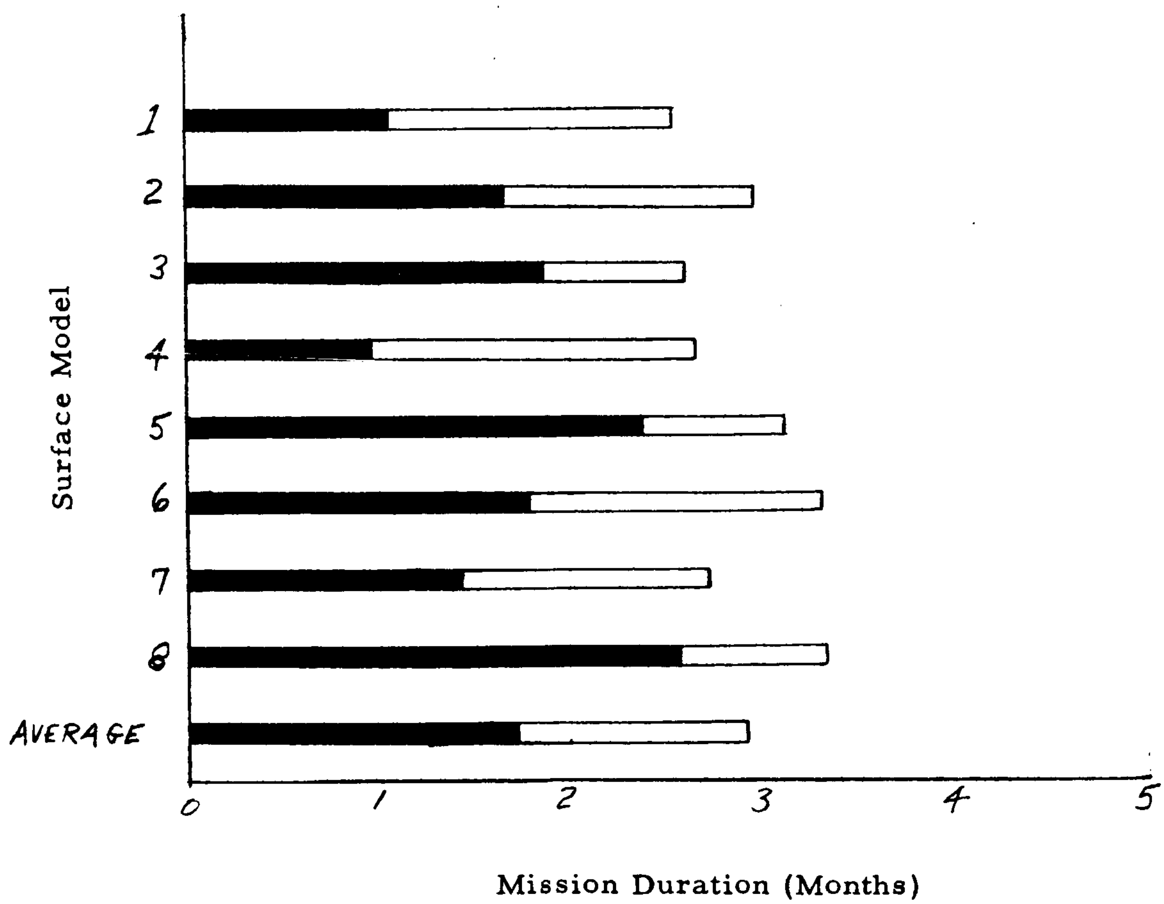

Figure 4-9 Mission Duration– 120 lb System

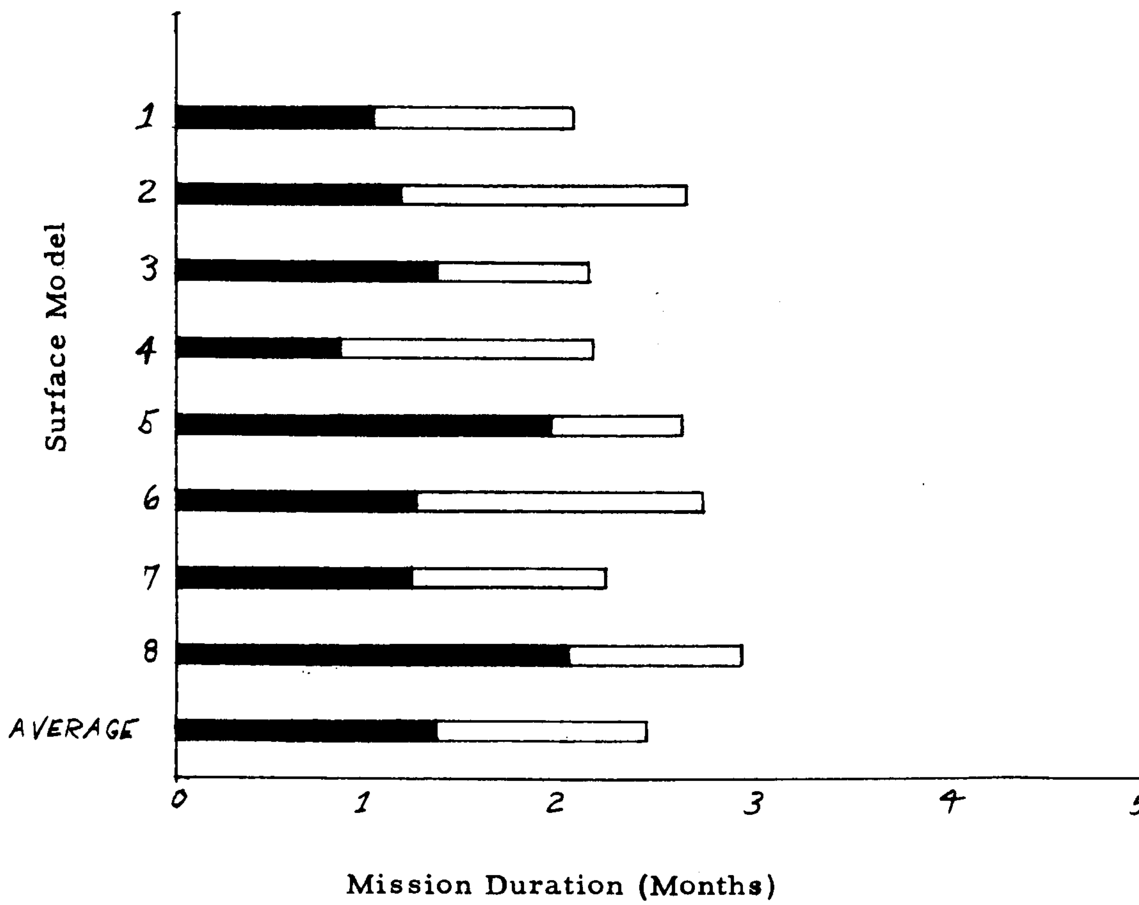

Figure 4-10 Mission Duration—130 lb System

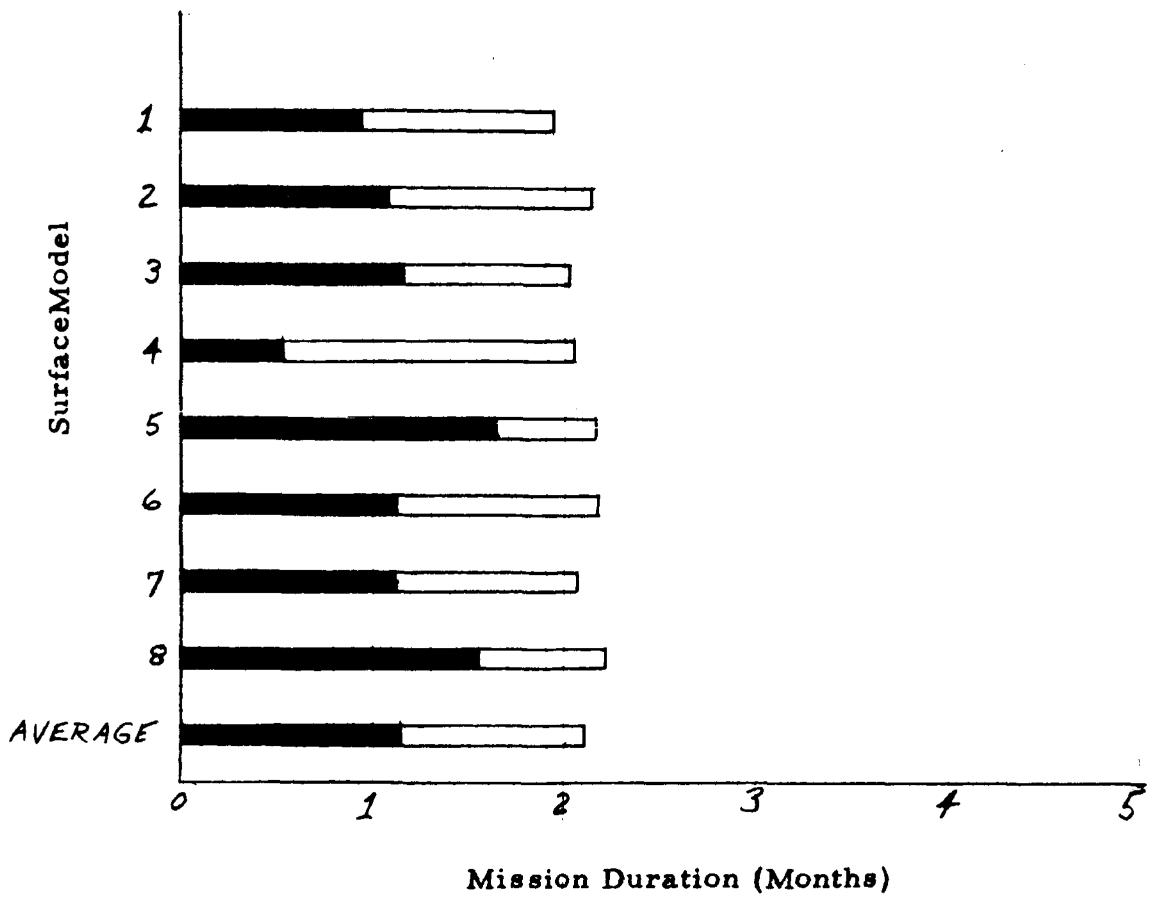

Figure 4-11 Mission Duration—140 lb System

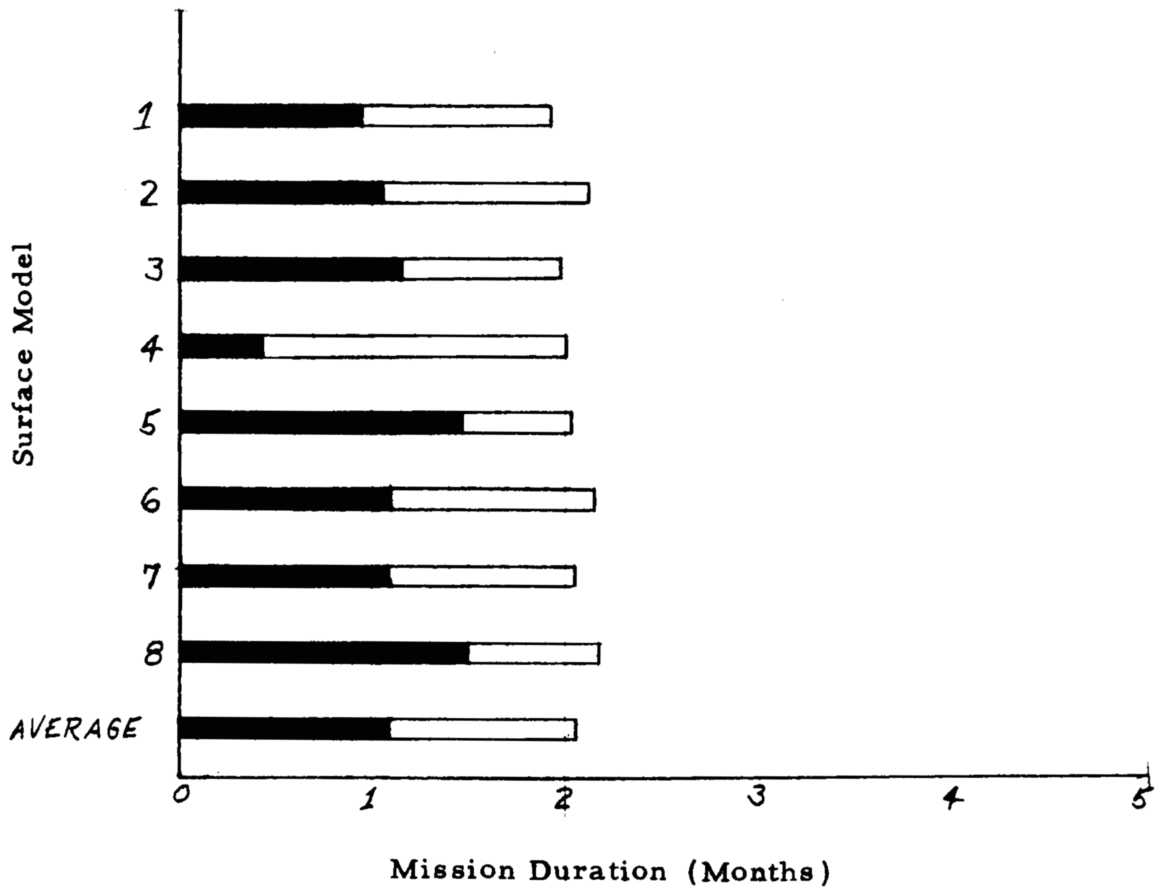

Figure 4-12 Mission Duration—150 lb System

SECTION 5

ENGINEERING TEST MODEL TEST RESULTS

The objective of the Engineering Test Model (ETM) was to demonstrate mobility, maneuverability, the principle of a floating pivot point, and limitations imposed upon mobility by the amount of power available.

The problem of scaling a test vehicle for earth (e. g., demonstration of a design for operation on the moon at 1/6 earth g) was solved by using a 1:1 scale for linear dimensions and mass. The choice of these scale factors resulted in the requirement to scale time in the ratio of $1:\sqrt{6}$ such that real-time in the tests represented only $1/\sqrt{6}$ real-time on the moon. Accordingly, all performance characteristics involving time such as power, velocity, accelerations, etc., were measured in the appropriate scale ratio.

The ETM is illustrated in Figures 5-1 and 5-2, and can be described briefly as follows:

1. 4-track vehicle

2. Tracks approximately 23 in. long by 3 in. wide

3. Track attachment point - The tracks are attached to the struts by means of an axle and strike plate which allows each track to be locked at 0° or $\pm 45^\circ$ with respect to the strut or free floating between stop limits (stops at either $\pm 30^\circ$ or $\pm 45^\circ$)

4. Tread - 0.25 inch silastic (foamed silicone rubber) bonded to metal rim

5. Track base - 20 in. (between center of struts

6. Track spacing - 28 in. (outside-to-outside of track, pairs)

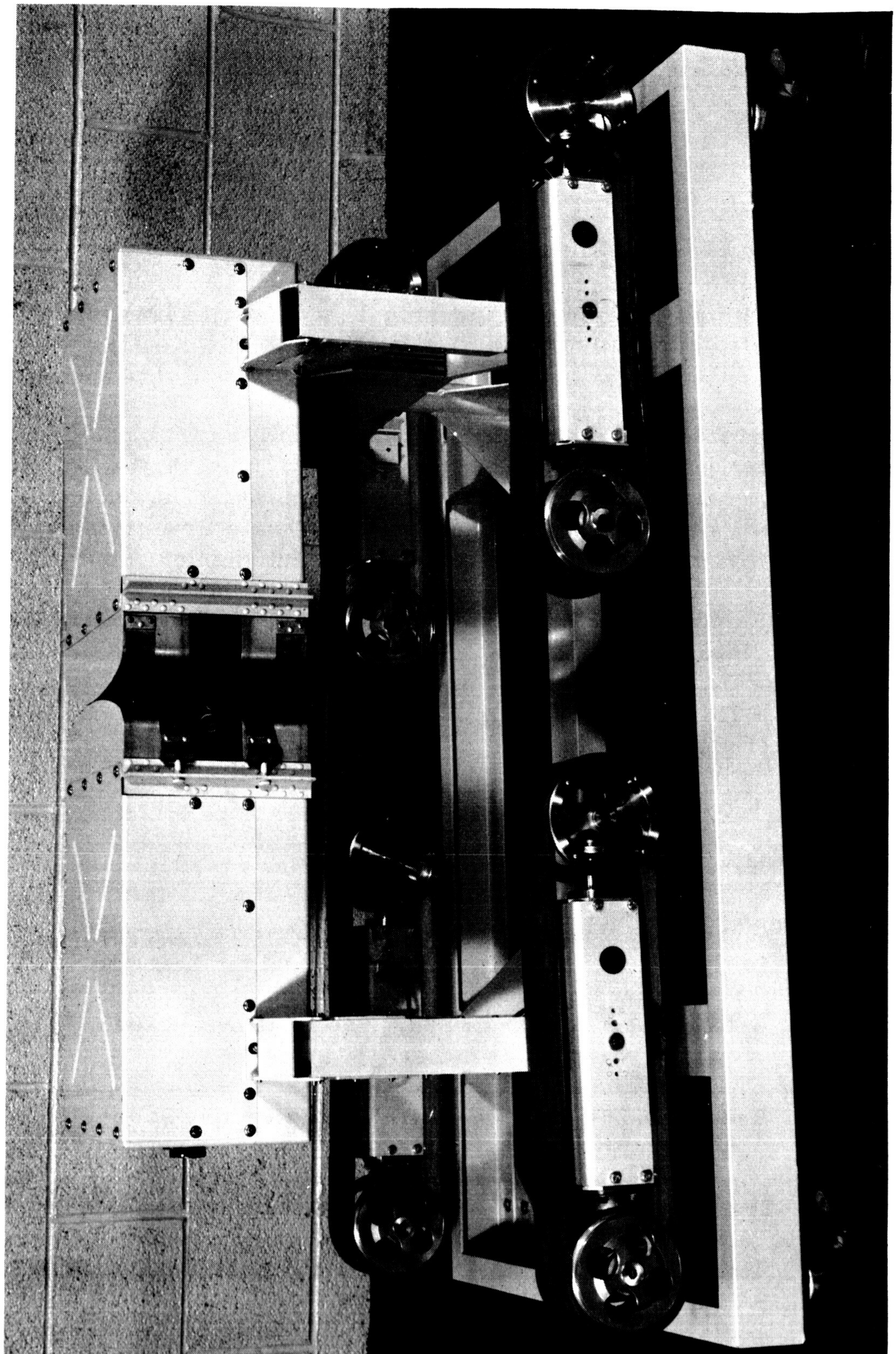

Figure 5-1 Side View, ETM

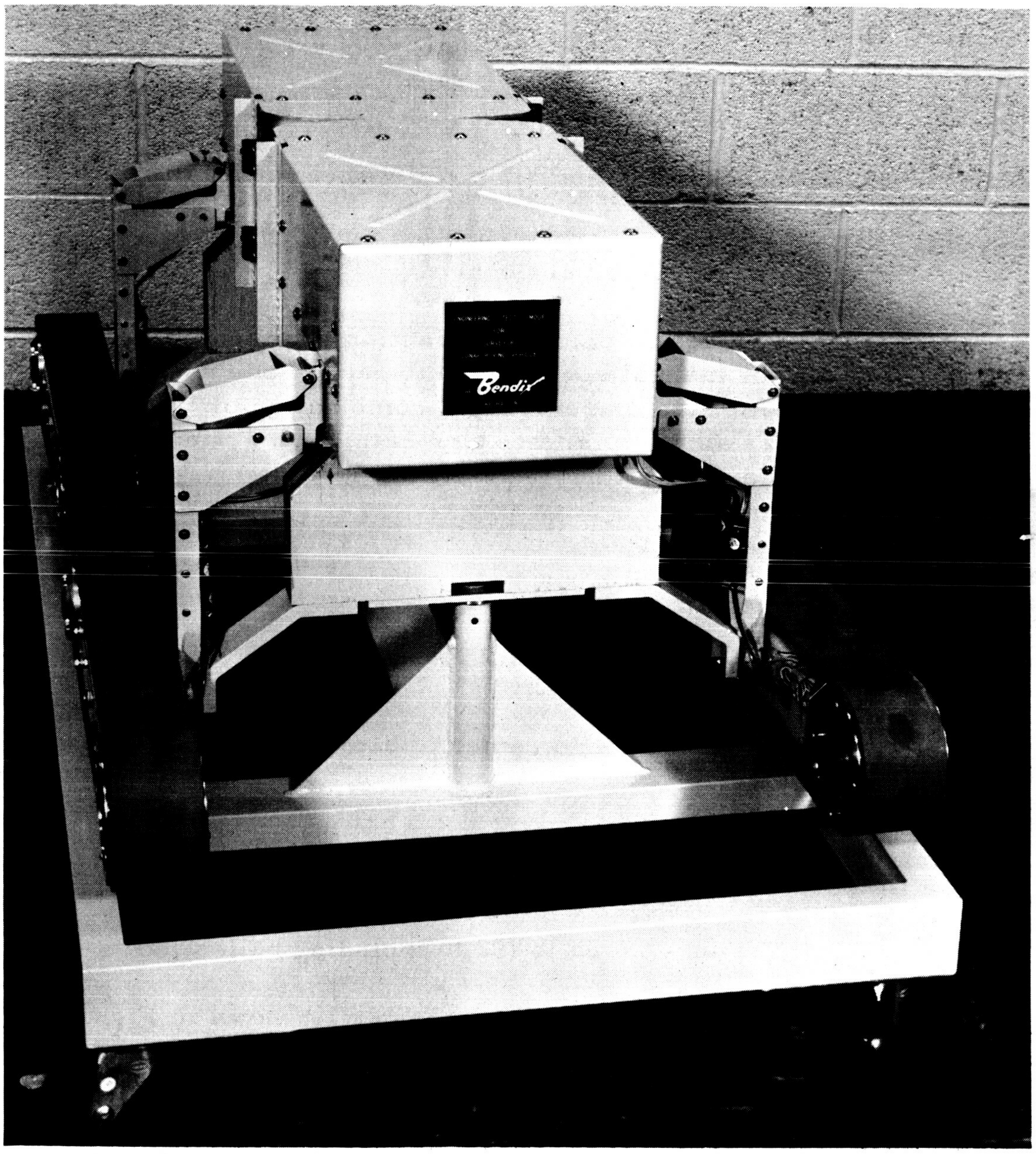

Figure 5-2 Front View, ETM

7. Body length - 38 in. (2 sections, 19 in. each)

8. Body width - 11 in.

9. Body height - 8 in.

10. Ground clearance of body - 12 in.

11. Drive - individual track (friction drive) furnished by motor gear head assembly

12. Vehicle speeds - operator selection of speeds listed below for manual control. Automatic mode uses V_1 for forward or reverse, a combination of V_1 and V_2 or V_1 and 0 to initiate turn rate, and V_1 and V_2 for steady-state turn.

    V_1 = 0.396 mph

    V_2 = 0.26 mph

    V_3 = 0.074 mph

13. Turn radius - 5 ft. to center of body in steady-state turn

14. Turn rate - variable, selected by operator on control console

15. ETM Weight - 77.25 lb (92 lb including ballast).

A photograph of the ETM control console is shown in Figure 5-3. Five major subassemblies were integrated into the single enclosure: control and display panel, signal conditioner panel, automatic control panel, DC power supply, and the AC power control equipment. The console interconnects with the ETM vehicle and strip chart recorder through an access cable entry panel at the rear of the console.

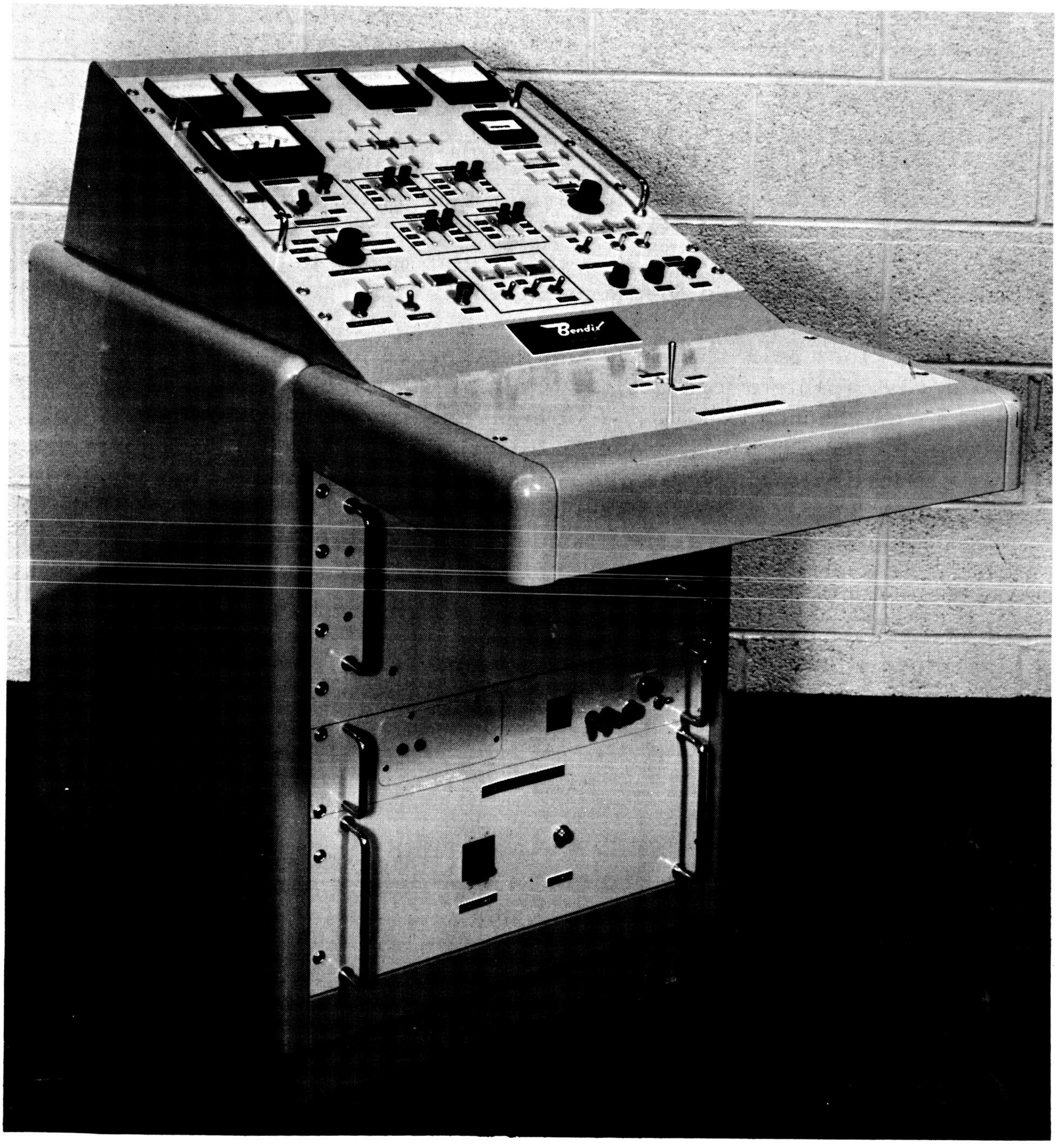

Figure 5-3 ETM Console Assembly

5.1 TEST COURSE DESCRIPTION

The test course used for engineering tests consisted of four 16 x 16 ft wooden decks, two 4 x 12 ft wooden decks, an adjustable step obstacle, dome-shaped obstacles, and an obstacle course consisting of random size rocks from 15 to 30 cm. in diameter. Two of the 16 x 16 ft decks were provided with various covering materials ranging from bare plywood through a sheet aluminum to obtain data on various friction coefficients. One of the two decks was adjustable in an angle up to 45° to allow evaluation of the ETM on slopes and obstacles on slopes.

The other pair of 16 x 16 foot decks were joined together with one of the decks capable of being tilted to a maximum inclination of 35°. These decks were bounded with a 2-foot high fence and filled to a depth of 12 inches with expanded Perlite at a nominal density of 7. lb / ft^3. This material had properties somewhat more critical in terms of vehicle design than the minimum "soft soil" model specified in EPD-98. A description of the characteristics of the Perlite is contained in Table 5-1. Exact scaling of the soil was not possible because of the non-linear relationship between the basic soil parameters. Expanded Perlite was chosen to match the more critical parameters of sinkage and cohesion coefficient of the soft-soil model. Variation in the sinkage exponent (n) from the ideal scale value did not materially affect the tests, since the total sinkage of the vehicle was limited to approximately 1 inch.

TABLE 5-1

SOIL PARAMETERS

Parameter	Lunar	Scale	Perlite
Sinkage coefficient (k)	0.083 psi	0.5 psi	0.39 ± .03 psi
Sinkage exponent (n)	1	1	0.58 ± .01
Grain size microns	50	50	700 (average)
Cohesion coefficient (c)	0 to 0.5	0-3 psi	0.012 psi
Angle of internal friction (ϕ)	20° to 35°	20° to 35°	29° to 32°

5.2 TEST RESULTS

5.2.1 Mobility

The vehicle motion could be controlled on the hard surface with various combinations of track speed and direction; but, on the soft soil, best control was accomplished by varying the speed of the tracks while they all drove in the same direction.

The vehicle could be turned with a five foot radius (to center of body) on a hard surface with slightly better performance in the soft soil. A scuff turn could be accomplished within the length of the vehicle on the hard surface by operating the inside tracks in reverse and the outside tracks in forward. The maximum slope that the vehicle could climb was 35° on a plywood surface, and 18° on the 7 lb/cu. ft. perlite soft soil. The angle of repose of the perlite on the test course was 26° which limited the soft soil slope climbing capability. Above 18° the forward motion of the vehicle was marginal, although the tracks were not exceeding the power limits, and therefore continued to turn. The ETM vehicle static stability limits were 80° in pitch and 42° roll.

5.2.2 Step Test

The results from the step test have been plotted in Figure 5-4. The perlite step was formed using wood for a riser.

5.2.3 Knife Edge Test

Tests were conducted with a 3/4" thick obstacle so that the front tracks would climb over the obstacle and were driving on the floor before the rear tracks started to climb the obstacle. The vehicle would climb over a 30-cm knife edge obstacle of plywood or roofing paper, and in the perlite it would climb over a 15-cm wood obstacle.

5.2.4 Crevice Test

The results from the crevice tests are presented in both tabular and plotted data, Figure 5-5 and Table 5-2.

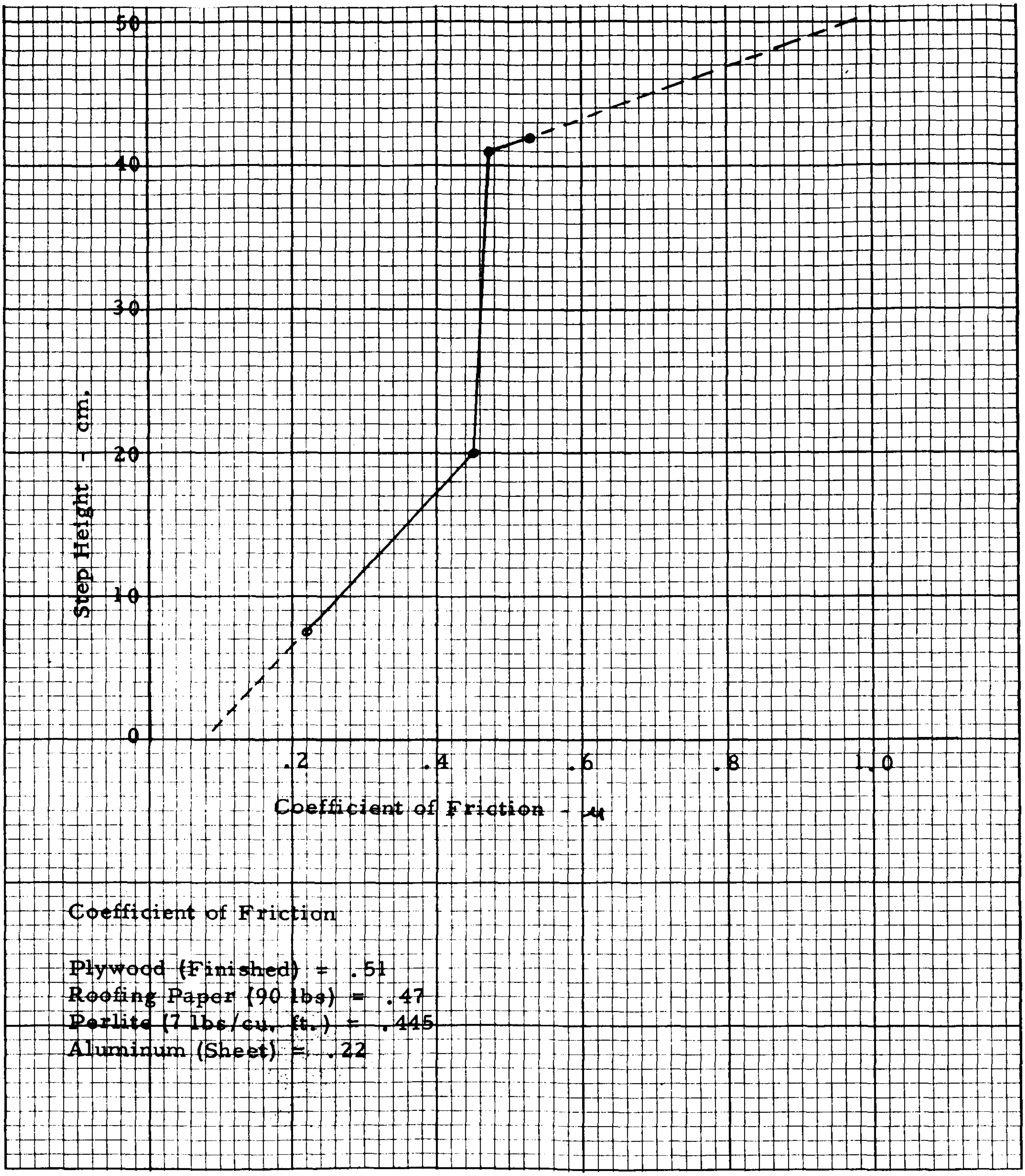

Figure 5-4 ETM Test Results of Step-Climbing Capability

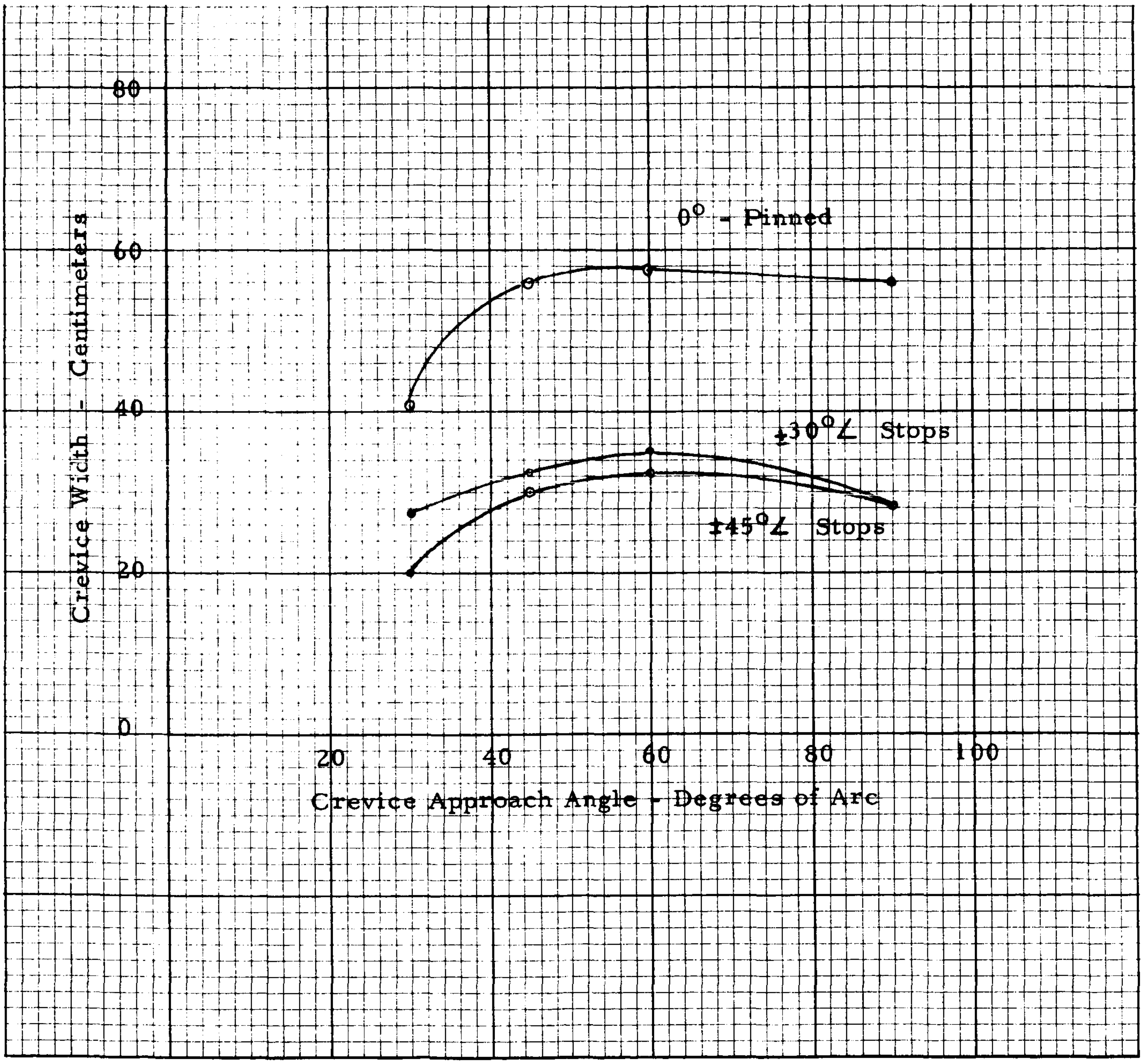

Figure 5-5 ETM Crevice-Crossing Test Results on Roofing Paper Surface

TABLE 5-2

CREVICE TESTS

(All Distances in Centimeters)

Test Course Surface	Crevice Approach Angle (°)	Direction		Track Adjustments					
				0° (Pinned)		±30° (Stops)		±45° (Stops)	
		Fwd	Rev	Crossed	Failed	Crossed	Failed	Crossed	Failed
Roofing Paper	30	X		41	43	28	30	20	22
	30		X	41	43	18	20	18	20
	45	X		56	58	33	35	30	32
	45		X	56	58	37	39	23	25
	60	X		58	60	35	38	33	35
	60		X	58	60	32	34	28	30
	90	X		56	58	28	30	28	30
	90		X	56	58	28	30	30	32
Plywood	30	X		52	54	32	34	25	27
	30		X	52	54	32	34	23	25
	45	X		57	59	33	35	32	34
	45		X	57	59	32	34	26	28
	60	X		58	60	32	34	30	32
	60		X	58	60	32	34	27	29
	90	X		56	58	29	31	27	29
	90		X	56	58	29	31	28	30
Aluminum	30	X		47	49	25	27	23	25
	30		X	47	49	20	22	19	21
	45	X		57	59	32	34	34	36
	45		X	57	59	30	32	30	32
	60	X		61	63	33	35	33	35
	60		X	61	63	32	34	30	32
	90	X		56	58	30	32	29	31
	90		X	56	58	28	30	28	30

5.2.5 Track Abort Test

The ETM will operate on the hard surface scuffing one track, but not in the soft soil where the track tends to dig in. With one track free wheeling, the ETM operates satisfactorily on the hard surface (both level and slope) and the level perlite. It would climb most 12-cm obstacles on a hard surface. With two tracks free wheeling, the vehicle operation was marginal and difficult to predict.

5.2.6 Random Obstacle Test

The ETM performance in the random obstacle test (consisting of a pile of rocks ranging in size from 16 to 30-cm in diameter) can only be evaluated subjectively due to the random nature of the course. It was observed that steering on steep slopes (15 to 30°) was difficult; the vehicle tended to follow a path of least resistance. Inclusion of a turn actuator might improve the operation; however, the gain vs the increase in weight for the actuator has not been thoroughly evaluated.

5.2.7 Power Limitations

Power limiting circuits were used to stop the ETM whenever the track motors exceeded the value scaled from the SLRV (the power scaling factor is $6\sqrt{6}$). As expected, these limiters prevented climbing, at the highest speed (V_1), slopes above 20° and maximum step obstacles. These tests were accomplished at lower speeds (V_2 and V_3). Power to the track motors of the ETM was supplied through speed control units duplicating, in most respects, the pulsating DC equipment planned for the SLRV. The test results verify the feasibility of this technique.

5.3 ETM MOBILITY EXTRAPOLATION

The parametric data used in Volume II for selection of the mobility concept included estimates of system weight for higher step-climbing capability. These estimates were based on a compatible design providing equal mobility under all design conditions, i.e., undercarriage clearance, lateral stability, steps, and crevices.

The parametric study indicated the superiority of a four-track design in the weight range of interest for the 100-lb SLRV. Because of weight constraints, an allocation of only 18 lb was made and a target of 30-cm step climbing capability was set for the design of the mobility subsystem. The actual values achieved by this design were 12.9 lb and approximately 40 cm (as demonstrated by the ETM).

For purposes of comparison, it should be noted that the parametric study included interconnecting structure (struts) as part of the mobility system weight, in addition to the weight of the tracks, drive mechanism, idlers, etc. This addition (1.44 lb for the present design) results in a comparable figure of 14.3 lb. Furthermore, the present design is not "compatible" in that it provides only 30 cm of undercarriage clearance and less than 40 cm lateral stability (depending on cg height). The crevice crossing capability, with tracks floating rather than pinned, is slightly less than 30 cm. Therefore, the struts will have to be made longer and controllable track locks added to make the present design compatible at 40 cm.

This philosophy can be used to extrapolate from the present design (validated by ETM tests) to heavier SLRV configurations with increased mobility or a greater allocation of weight to mobility in the 100-lb system, but at the sacrifice of other system capabilities. Figure 5-6 shows the four-track data for such an extrapolation. The dotted curve is the parametric trend used in the original system concept selection. The lower solid curve shows revised data based on subsequent design and test information for a compatible design.

It does not appear necessary to provide more than 50-cm undercarriage clearance for vehicles with greater step-climbing capability because such hazards may be detected and avoided by reasonable operator control. Therefore, an upper solid curve is presented for limited designs having only 50-cm undercarriage clearance and equivalent lateral stability.

These curves include an estimate of the weight required for folding the struts to fit in the Surveyor envelope when the dimensions of the present (100-lb) design are exceeded. No consideration is given to the reliability of such joints in the extrapolation analysis.

The application of these curves is illustrated by an example. To find the effect on mobility system weight for a change in mobility requirements, assume that a 75-cm step-climbing capability is selected in conjunction with a 50-cm undercarriage clearance. The corresponding point on the limited design curve gives a mobility system weight of 32.5 lb, approximately 18.2 lb more than the present design.

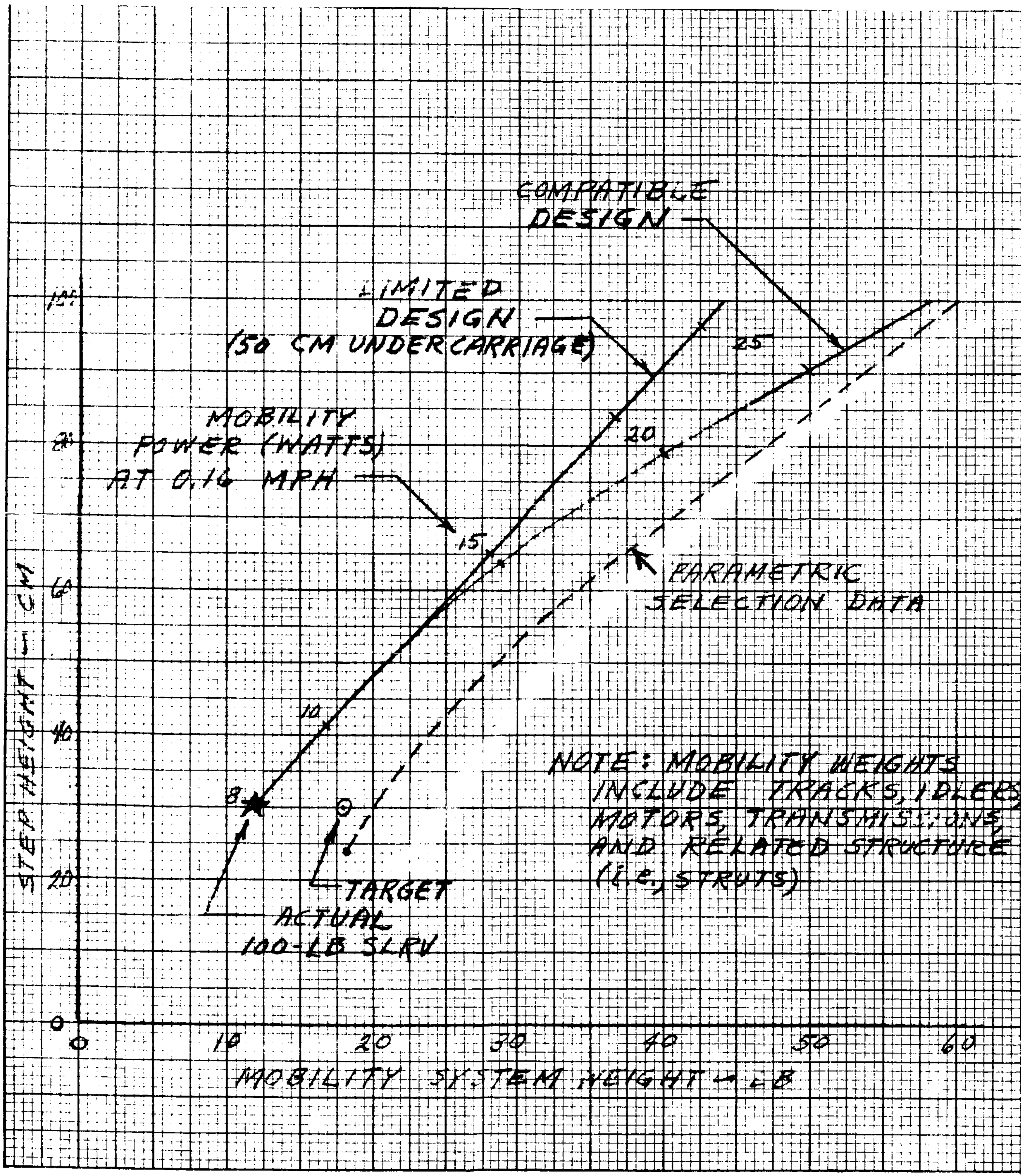

Figure 5-6 Four-Track Vehicle Mobility Extrapolation

Based on ETM test results, it is anticipated that such a four-track design is feasible. If there were no changes in other subsystems, the SLRV would weigh 109.9 lb, plus the 8.3 lb Surveyor-mounted equipment allowance.

Other weight changes might be encountered; e.g., increased structure and deployment support equipment for the heavier SLRV. However, it is also possible that compensating reductions (trade-offs) could be made in communications or navigation equipment.

The power requirements for increased mobility should be noted. Values indicated on the extrapolation chart yield an estimate of 17.5 watts for the 75-cm limited design, if the top speed of 0.16 mph is maintained. This increase of 9.5 watts over the reference design would call for a power supply weight increase of approximately 5 lb.

Thus, the extrapolation chart provides a means of interpreting the ETM test results in terms of larger vehicles, where large refers to the scale of the mobility system.